PB84-169622

Improved Street Sweepers for Controlling Urban Inhalable Particulate Matter

Air Pollution Technology, Inc., San Diego, CA

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

Feb 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-169622

EPA-600/7-84-021
February 1984

IMPROVED STREET SWEEPERS FOR CONTROLLING URBAN INHALABLE PARTICULATE MATTER

by

Seymour Calvert, Harry Brattin and Sudarshan Bhutra

A.P.T., Inc.
4901 Morena Blvd., Suite 402
San Diego, CA 92117

January 1984

EPA Contract No. 68-02-3148

EPA Project Officer: William B. Kuykandal
Industrial Environmental Research Laboratory
Office of Environmental Engineering and Technology
Research Triangle Park, NC 27711

Prepared for:

U.S. Environmental Protection Agency
Office of Research and Development
Washington, D.C. 20460

Best Available Copy

REPRODUCED BY
NATIONAL TECHNICAL INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-84-021	2.	3. RECIPIENT'S ACCESSION NO. PB84 169622
4. TITLE AND SUBTITLE Improved Street Sweepers for Controlling Urban Inhalable Particulate Matter		5. REPORT DATE February 1984
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) S. Calvert, H. Brattin, S. Bhutra, and D. Ono		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS A. P. T., Inc. 4901 Morena Boulevard, Suite 402 San Doego, California 92117		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. 68-02-3148
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 8/79 - 7/81
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is William B. Kuykendal, Mail Drop 61, 919/541-7865.

16. ABSTRACT The report gives results of an experimental program to develop design modifications that can be used to improve the ability of municipal street sweepers to remove inhalable dust particles from streets. (Dust emissions from paved roads are a major source of urban inhalable particulate matter.) A commercial regenerative air sweeper was modified. Major modifications included a charged spray scrubber for fine particle collection, and a gutter broom hood to help contain redispersed dust particles. The upgraded sweeper proved effective in eliminating dust plumes during sweeping and giving cleaner streets.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Streets Brushing Dust Pavements Plumes Charging	Spraying	Pollution Control Street Sweepers Particulate	13B 13H 11G 21B 14G

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 128
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

ABSTRACT

Dust emissions from paved roads are a major source of urban inhalable particulate matter. A.P.T. performed an experimental program to develop design modifications which can be used to improve the ability of municipal street sweepers to remove inhalable dust particles from the street.

A commercial regenerative air sweeper was modified. Major modifications include a charged spray scrubber for fine particle collection and a gutter brom hood to help contain redispersed dust particles. The upgraded sweeper was proven to be effetive in eliminating the dust plume during sweeping and giving a cleaner street.

CONTENTS

Page

Disclaimer . . . .
Abstract. iii
List of Figures vi
List of Tables. x
Abbreviations xi
Nomenclature xii
Acknowledgment xiv

Sections

1. Summary 1
  Introduction 1
  Objective. 2
  Approach 2
  Results 3
  Conclusions. 10
  Recommendations. 11
2. Introduction. 12
  Urban Fugitive Dust Emissions. 12
  Street Sweepers. 12
  Proposed Method for Sweeper Improvement 15
  Research Program Outline 20
3. Background Information. 23
  Street Dust Loading and Size Distribution. . . . 23
  Street Sweepers. 34
4. Preliminary Experiments 49
  Air Flow Near Broom 49
  Redispersed Street Dust Concentration
    and Size Distribution 50
5. Sweeper Modifications 59
  Tymco Model 600 Street Sweeper 59
  Conceptual Design. 62
  Preliminary Experiments. 62
  Detailed Design 85

CONTENTS

Page

6. Road Tests. 90
    - Gutter Broom Hood. 90
    - Vent Air Rate. 91
    - Particle Size Distribution and Concentration at Scrubber Inlet. 94
    - Sweeping Efficiency. 106
    - Scrubber Efficiency. 117

7. Recommendations 125

References. 126

LIST OF FIGURES

Page

Figure 1. Street debris accumulation rates (URS Research Company, 1974). 14

Figure 2. SCAT system for controlling reentrained dust from paved roads 18

Figure 3. Deposition and removal processes (Axetell and Zell, 1977). 24

Figure 4. Rate of reentrainment of particulates from street surfaces (Pitt, 1978) 29

Figure 5. Reentrainment of dust by vehicles as a function of amount of street debris (Pitt, 1978). 30

Figure 6. Size distribution of suspended dust in vicinity of paved streets. 32

Figure 7. Particle size distribution near road (Pitt, 1978). 34

Figure 8. Three wheel broom sweeper 40

Figure 9. Vacuum assisted sweepers. 41

Figure 10. Debris picked up vs. brush speed (Horton, 1968). 43

Figure 11. The effect of pattern on residual debris (Horton, 1968) 44

Figure 12. The sweeping pattern vs. stiffness for synthetic broom fibers (Horton, 1968) 45

Figure 13. Air velocity near broom of Mobil sweeper. Wind velocity: 0.5 m/s. 51

Figure 14. Particle size distribution of dust dispersed by a mechanical street sweeper 52

Figure 15. Schematic diagram of sampling equipment for particle size distribution data 54

Figure 16. Particle size distribution of dust dispersed by a vacuum (regenerative air) sweeper. Data are compared with previously reported particle size distributions . . . 56

LIST OF FIGURES (continued)

Page

Figure 17. Comparison of cumulative mass concentration of dust dispersed by street sweepers (dry sweeping) 57
Figure 18. Side view of TYMCO vacuum (regenerative air) sweeper. 60
Figure 19. Schematic diagram of TYMCO Model 600 regenerative air system 61
Figure 20. Process diagram of improved street sweeper. . 63
Figure 21. Predicted penetration for 300 μm diameter spray drop scrubbing 67
Figure 22. Predicted penetration for 300 μm diameter spray drop scrubbing 68
Figure 23. Predicted efficiency for coulombic attraction and inertial impaction 71
Figure 24. Trajectories for water drops in air 72
Figure 25. Collection efficiencies of neutral and charged drops for 0.6 μmA diameter particles. 73
Figure 26. Experimental apparatus for measuring particle collection efficiency of a charged spray scrubber. 77
Figure 27. Measured spray scrubber particle penetration, Test 1 78
Figure 28. Measured spray scrubber penetration 79
Figure 29. Measured spray scrubber penetration 80
Figure 30. Measured spray scrubber penetration 81
Figure 31. Measured particle charger and spray scrubber penetration. 82
Figure 32. TYMCO street sweeper and trailer. 86
Figure 33. Scrubber shell. 87
Figure 34. Plan view of the sampling platform. 89

LIST OF FIGURES (continued)

Page

Figure 35. Schematic diagram of street sweeper flow circuit. 92
Figure 36. Particle size vs. mass concentration of dust at scrubber inlet in an industrial area 95
Figure 37. Particle size vs mass concentration of dust at scrubber inlet in a commercial area. 96
Figure 38. Particle size vs. mass concentration of dust at scrubber inlet in a residential area. 97
Figure 39. Particle size distribution of dust at scrubber inlet in an industrial area. 98
Figure 40. Particle size distribution of dust at scrubber inlet in a commercial area 99
Figure 41. Particle size distribution at scrubber inlet in a residential area 100
Figure 42. Scrubber inlet dust concentration 103
Figure 43. Particle size distribution. 104
Figure 44. Effect of vent air flow on scrubber inlet dust concentration. 105
Figure 45. Uniform airflow vacuum nozzle 108
Figure 46. Air jet nozzle. 109
Figure 47. Air jet nozzle performance. 110
Figure 48. Test strip layout for street sweeping efficiency measurement. 112
Figure 49. Street dust distribution before and after sweeping. 113
Figure 50. Street dust distribution before and after sweeping. 114
Figure 51. Overall street sweeping efficiency. 116
Figure 52. Street sweeping efficiency. 118
Figure 53. Street sweeping efficiency. 119

LIST OF FIGURES (continued)

Page

Figure 54. Scrubber performance. 121
Figure 55. Scrubber performance. 122
Figure 56. Scrubber performance. 123

LIST OF TABLES

Page

Table 1. Dust deposition and removal rates from paved roads (Axetell and Zell, 1977). 13
Table 2. Cleaning efficiency of street cleaning methods (Sartor and Boyd, 1972) 16
Table 3. Street dust surface loading (Sartor and Boyd, 1972) 26
Table 4. Size distribution of street dirt and dust (Sartor and Boyd, 1972). 27
Table 5. Vehicle emission rates on paved roads 31
Table 6. Technical features on street sweepers 35
Table 7. Information on street sweepers. 38
Table 8. Sweeper efficiency with respect to particle size (Sartor and Boyd, 1972) 46
Table 9. Total solids street cleaner removal effectiveness by particle size (Pitt, 1979) 47
Table 10. Air flow characteristics of the TYMCO sweeper 65
Table 11. Average collection efficiencies of drops and spray penetrations. 75
Table 12. Data on fine spray nozzles. 84
Table 13. Summary of sampling results from Los Angeles area. 101
Table 14. Summary of scrubber tests 120

LIST OF ABBREVIATIONS

IPM - inhalable particulate matter
GB - gutter broom
SCAT - Spray charging and trapping
ID - Inside diameter
OD - Outside diameter
PVC - polyvinyl chloride
Sch - pipe schedule
OAQPS - Office of Air Quality Planning & Standards

NOMENCLATURE

C = Coulomb

C' = Cunningham slip factor, dimensionless

d_c = collector diameter, cm or μm

d_d = diameter drop, cm or μm

d_p = particle diameter, cm or μmA

d_{pa} = aerodynamic particle diameter, μmA

f_A = gas flow cross-section covered by spray, fraction

k_f = gas dielectric constant

K_c = Coulombic attraction parameter, dimensionless

K_p = inertial impaction parameter, dimensionless

$\overline{Pt}$ = overall particle penetration, fraction

Pt_d = particle penetration for diameter "d_{pa}", fraction

Q_c = collector charge, C

Q_p = particle charge, C

Q_G = gas flow rate, cm^3/s

Q_L = liquid flow rate, cm^3/s

R_d = drop range (distance traveled by drop relative to gas), cm

u_r = gas velocity relative to collector, cm/s

u_G = gas velocity, cm/s

u_{GO} = initial drop velocity relative to gas, cm/s

u_O = initial velocity, cm/s

x = coordinate in gas flow direction, cm

NOMENCLATURE (GREEK)

σ_g = geometric standard deviation, dimensionless

η = instantaneous single drop collection efficiency, fraction

$\bar{\eta}$ = average collection efficiency over drop range, fraction

ρ_p = particle density, g/cm^3

ACKNOWLEDGMENTS

A.P.T., Inc. expresses grateful appreciation to the following individuals for their contribution during this study:

Dr. Dennis C. Drehmel	former Project Officer, EPA, IERL/RTP
Mr. William Kuykendal	Project Officer, EPA, IERL/RTP

Sincere gratitude goes to the City of San Diego and the City of Anaheim for providing street sweepers and operators during this project.

Section 1

SUMMARY

INTRODUCTION

Dust emissions from paved roads are a major source of urban air pollution. Draftz (1978) estimated that 40 to 70% of the total suspended particulate matter in many urban areas comes from dust particles redispersed by road traffic. Pitt (1979) estimated that city streets can contribute from 5 to 50 μg/m³ of particulate matter to the urban air.

The existing types of street sweepers include broom, vacuum, regenerative vacuum, and water flushing sweepers. These generally have low-to-moderate efficiency for removing inhalable particulate matter (IPM) from streets and test data scatter widely. Buchwald and Schrag (1967) sampled the air inside the driver's cab and determined that there is a serious exposure to respirable dust. Closing the windows and the use of a cyclone separator for dust collection had small effect on respirable dust concentration in the cab.

It is clear that urban street dirt can cause air pollution, water pollution from rain water runoff, and an occupational hazard for the sweeper operator. When evaluated with regard to IPM removal, each of the conventional types of sweepers has a significant deficiency, as indicated below.

Type of Sweeper	Deficiency
Broom	Disperses IPM while sweeping.
Vacuum	Either emits IPM or must clean a large volume of vent air. Gutter broom disperses IPM into air.
Regenerative Vacuum	Disperses IPM while sweeping.
Water flush	Moves IPM to gutter and causes water pollution.

OBJECTIVE

Under E.P.A. contract, A.P.T. has conducted a research and development program with the primary objective of developing practical means for improving the efficiency of a suitable street sweeper for the removal of IPM from urban streets.

A.P.T. evaluated the problem and proposed to develop a street sweeper which would use a regenerative air flow system, gutter broom hooding, and a low-volume scrubber on a vent air stream. The use of a vent air stream would permit a positive inward flow of air from the sweeping area into the sweeper body rather than allowing this dusty air to be dispersed. The applicability of the SCAT (Spray Charging and Trapping) system was to be investigated.

The SCAT system uses combinations of air curtaining, hooding, and spray scrubbing (with or without electrostatic augmentation) to capture and retain particles for subsequent disposal. Specific circumstances dictate the SCAT features which are used in each case.

Additional objectives of the program were to:

1. Build a modified street sweeper and demonstrate its capabilities for urban street sweeping.
2. Develop and use methods for evaluating sweeping efficiency.

APPROACH

The general approach of the program was consistent with the premise that a suitable scrubber could be designed if one knew what air flow rate and particle collection capability were required. In other words, much more was known about scrubber design than about street sweeping in terms of IPM control parameters. Consequently, the main effort was placed on determining:

1. Background information on street sweeping.
2. The street sweeper best suited for study.
3. A tentative set of design criteria to use for designing the experimental street sweeper, including:
    a. Air flow rates required to control dust emissions.
    b. The total air flow rate which has to be scrubbed.
    c. Particle size distribution and particle concentration in the uncontrolled effluent air.
    d. Utilities limitation.
4. Design concepts for the modifications needed for IPM control.
5. An experimental procedure for determining the efficiency of removing IPM from urban streets.

A limited effort was expended on charged spray scrubbing and scrubber design. Some experimental work was done to confirm earlier experiments and to evalute concepts for atomizers and drop chargers which could produce smaller charged drops than used in previous work. The further development of a mathematical model for particle collection by charged spray also received some effort.

RESULTS

Literature Search

A literature search and interviews of qualified persons were conducted to determine:

1. The nature of dirt on paved streets, including information on the sources of particulate matter, the methods of deposition, and various methods of removal.
2. The prevalent types of street sweepers available, their cost, and the potential for improving them.
3. Methods for sampling and analysis of the IPM on the street and in the air.

There is abundant literature on street dirt and its contribution to air and water pollution. There is, however, very little on the subject of street sweeper efficiency as a function of dust particle size. Brookman and Martin (1979) present an extensive literature review and recommendations for research areas. Some of the works which provide useful quantitative information are those of Axetell and Zell (1977), Cowherd et al. (1977), Draftz (1978), Pitt (1979), Sartor and Boyd (1972), and Sehmel (1973).

At the time the research began, broom sweepers were the type most commonly used. However, the trend appeared to be toward the use of regenerative vacuum sweepers, so this was the type selected for the present research.

Street sweeping effectiveness has been determined in several ways, such as:

1. Ambient air was sampled upwind and downwind from the street to determine the contribution of dust from the street (e.g., Cowherd et al., 1977, and Pitt, 1979).
2. Street dirt loading was measured by vacuum-cleaned sample areas before and after sweeping (e.g., Cowherd et al., 1977).
3. Street dirt loading was measured by a combination of sweeping and water-flushing sample areas before and after street sweeping (e.g., Sartor and Boyd, 1972).

Regenerative Vacuum Sweeper

A regenerative air vacuum sweeper uses a gutter broom to brush the curb and throw the dirt from the curb toward the center. A center plate is used to stop the thrown dirt so that it piles up at the center of the sweeper path. As the sweeper moves forward, the debris piles can be taken up by the vacuum pick-up head, which extends almost the entire width of the sweeper. Blast orifices in the pick-up head direct air jets at the street surface to dislodge the dirt, which is then sucked into the hopper through the vacuum hose. The air and the dirt are separated in the hopper. The air then recycles back to the blast orifices through the blower and the pressure hose.

Conceptual Design

Observation of street sweeper operation clearly showed that gutter broom and leakage from the "pickup head" were the major sources of IPM emissions from the regenerative vacuum sweeper. The following design concepts were conceived during sweeper operation observations. The dust clouds around the gutter broom can be controlled by installing a hood over the broom and venting to the hopper. Since the hopper is under vacuum, an induced flow of air will convey the contained dust to the hopper.

Dust clouds in the pick-up head area were observed to occur when the pick-up head travels on uneven street surfaces. Pick-up head dust clouds can be eliminated by increasing the vacuum in the vacuum hose, which causes an increase in the inward flow into the pick-up head.

To balance the air streams from the gutter broom hood and the pick-up head, a portion of the air from the sweeper blower must be vented. This vent air stream is cleaned by a scrubber.

Preliminary Experiments

Preliminary experiments were done to obtain design information for the vent air scrubber system. Several street dust samples were taken from the plumes dispersed by broom and vacuum type sweepers. The representative particle size distribution had a geometric mean diameter of 4 μmA and geometric standard deviation of 2.

Predictions of scrubber efficiency based on the preliminary information on street dust size indicated that to achieve a minimum of 90% efficiency with an uncharged spray scrubber system would be impractical due to high water consumption. The required efficiency can be achieved with a charged system at a liquid flow rate of 0.4 l/m^3 (3 gal/Mcf) if a fine water spray is used (d_d

<100μm). Experiments on charged spray scrubbing were conducted to verify and extend the results of previous studies.

Detailed Design

The basic sweeper was analyzed for air flow and dirt conveyance. Extra ducting was needed to transport the vent air from the recirculating airflow system to the scrubber. Hoods were designed to contain the dust generated by the gutter brooms, and ducting was designed to carry this dirt to an appropriate place in the hopper.

It was necessary to develop a hood arrangement that allowed normal broom operation, and also reduced fugitive broom emisions to an acceptable level. A hood that completely encloses the broom was built, but was abandoned due to its poor performance. An abbreviated hood, which is similar to an air curtain distribution manifold, was later designed to cover the forward portion of the broom. This hood allows brushing on the curb side and operates with a high velocity suction air flow similar to a vacuum cleaner. It also uses the interaction of the rotating broom and street dirt to capture dust. The captured dust is conveyed to the main hopper with piping and flexible hose. A damper valve in the pipe section controls the air flow from the hood to the hopper.

Suction air flow at the pick-up head was increased by venting a portion of the air at the pressure hose. In order to design the vent air scrubber and the gutter broom hood, the required air flow rate was estimated from industrial ventilation practice to be about 28 to 56 m³/min (1,000 to 2,000 cfm) vented through the scrubber.

The sweeper has a blower which the manufacturer rated at 280 to 340 m³/min (10,000 to 12,000 cfm). While its capacity proved to be only 50% of the rating, it was adequate for venting about 30 m³/min and providing effective dust pickup in the hood.

The scrubber was designed for a maximum flow rate of 56 m³/min (2,000 cfm). A wire and rod type particle charger was built into the scrubber to pre-charge the particles. Downstream from the particle charger were four pin type spray nozzles. The spray was charged by induction with the nozzles maintained at ground potential and a high voltage grid in front of them.

A 15 cm (6 in.) thick knitted mesh entrainment separator was designed to remove water drops as well as large solid particles. The air velocity at the upstream face of the entrainment separator was increased by blocking about 50% of the flow area so that the cut diameter of the entrainment separator would be 3 μmA.

In an actual system, the scrubber could be located inside the hopper. For purpose of sampling and easy access, the scrubber was mounted on top of the sweeper and water was drained into the hopper.

The scrubber needed about 0.4 l/m^3 (3 gal./Mcf air handled). For convenience, this translates to a 0.76 m^3 (200 gal.) capacity to allow once-through operation, and a reasonable time between refills. The sweeper came with a 0.12 m^3 (30 gal.) tank. An auxiliary tank with capacity of 0.64 m^3 (170 gal.) was built and mounted on the sampling trailer.

The sweeper came equipped with a piston water pump which can provide 0.4 l/min (3 gpm) at 3,450 kPa (500 psi). For the first experimental sweeper, it was assumed that the existing water pump would suffice and that once-through water use would be acceptable.

The sampling system provides for the measurement of airflow from the gutter brooms to the scrubber inlet. Particle size and concentration were measured with cascade impactors. Sample ports were provided for the scrubber inlet and outlet at locations at least 8 duct diameters from upstream transitions or bends. Sample trains of the type used for EPA Method 5 were used. Scrubber and gutter broom airflow rates were measured with Venturi meters and were controlled by dampers.

The positive displacement water pump was calibrated in terms of auxiliary engine speed. Additional utilities (such as the electrical power supplies for sampling pumps and scrubber charging, water tank, transfer pump, sampling personnel station, and platform for sampling trains) were placed on a trailer pulled by the street sweeper.

EXPERIMENTS

Vent Air Rate

To minimize the scrubber size and water consumption, the air flow to be vented through the scrubber should be kept at a minimum. However, the air flow should not be so low that dust puffs occur around the gutter broom and the pickup head.

The minimum air flow needed to be vented through the scrubber to prevent the occurrence of dust puffs was determined when the gutter broom hoods were turned either ON or OFF. When ON, the air flow in each hood was maintained at 0.17 m^3/s (350 acfm), which was the minimum required flow for satisfactory hood operation.

It was found that the minimum air flow to be vented through the scrubber to prevent dust puffs with the gutter broom hoods OFF was about 0.33 m^3/s (700 acfm), and about 0.38 m^3/s (800 acfm) with the gutter brooms ON.

Street Dust Sampling

Full scale operation of the sweeper and auxiliary equipment was first done in San Diego to observe the modified components in use, and to provide more data on the nature of street dirt. Later, as the apparatus was refined, additional samples were gathered on other streets, and eventually more were gathered in heavy industrial areas in Los Angeles.

Sampling results showed that the concentration and particle size distribution vary greatly from location to location. Sampling results agree with visual observations in that dirtier streets resulted in higher particle concentrations and larger particles.

Street samples collected indicate a difference in characteristic size dirt when neighborhoods are considered. The major distinction noticed between neighborhoods is the amount of traffic; street dirt is reduced in size by continuous traffic.

The vent rate through the scrubber affects the mass concentration at the scrubber inlet. A higher vent rate resulted in a higher mass concentration.

Sweeping Efficiency Measurement Method

To determine the sweeping efficiency of the sweeper, a measurement method is required that measures the amount of dust that can be dispersed into the ambient air by the mechanisms actually occurring on street. The mechanisms of street dust removal are (Brookman and Martin, 1979):

1. Reentrainment (by air currents around moving vehicles).
2. Wind erosion (similar to 1, but due to natural air currents).
3. Displacement (similar to 1, re-deposition near street).
4. Rainfall runoff.
5. Street cleaning.

The first three mechanisms result in airborne dispersal of street dirt, so the sampling method should measure the amount of IPM which can be dispersed by these.

Preliminary experiments were performed to measure street dust density with a brush-type vacuum cleaner, as performed by Dahir and Meyer (1974). The dust on the street was first loosened with a brush, and then taken up and filtered by the vacuum cleaner. The dust density (mass/unit street area) was determined from filter weight gain.

This method was found to have several deficiencies. The vacuum cleaner can remove dust which is deposited deeply in cracks and is not normally reentrained. Further, the amount of dust vacuumed increases with each pass of the vacuum nozzle; therefore, there is no logical end point for sampling.

To simulate the re-entrainment mechanisms, a new method was developed that uses a vacuum cleaner with a modified pickup nozzle shaped to create a uniform 97 km/hr air flow field at the street surface. The dust dislodged by the airflow is sucked into the vacuum and filtered by the vacuum bag.

Efficiency Data

Street sweeping efficiency was determined by measuring the street dust concentration before and after sweeping. The street was divided into strips of equal area for dust concentration measurements before and after sweeping. Each strip was further sub-divided into the gutter broom area and the pick-up head area. Street dust is concentrated in the gutter area. The street sweeper efficiency were calculated from the measured street dust concentration before and after sweeping. The overall sweeping efficiency ranged from 80% to 98% in the gutter broom area and 75% to 90% in the main pick-up head area. Large particles were removed from the street at higher efficiencies. Particles with diameter smaller than 2 umA stayed on the ground in the gutter broom area after sweeping.

The performance of the modified sweeper was compared to that of a regular sweeper visually at a construction site. The modified sweeper not only drastically reduced the dust clouds around the sweeper, it also gave a cleaner street. A cleaner street will reduce the fugitive street dust emission.

Scrubber Efficiency

A few experiments were done in the laboratory to determine the collection efficiency of the spray scrubber on the sweeper. It has an overall collection efficiency of 80% on dust with mass median diameter of 2.0 umA and geometric standard deviation of 2.0 when the scrubber was un-augmented.

CONCLUSIONS

The feasibility of applying SCAT to the control of fugitive road dust emissions was proven. A regenerative vacuum sweeper is ideally suited to the SCAT technique. as it allows a discharge stream of air to be cleaned and recycled into the atmosphere. This feature reduces the size and power requirements for control of fugitive emissions of inhalable particle emissions.

Gutter broom dust emissions can be substantially improved with an advanced, interactive gutter broom hood. Since most of the dirt is in the gutter, this improvement is very significant. Additional power requirements for the SCAT system are minimal. Existing standard equipment pumps, blowers, and auxiliary power are sufficient to do the job.

RECOMMENDATIONS

A superior street sweeping machine has been developed for reducing particle emissions from paved streets. This street sweeper has been subjected to a limited testing program in San Diego and Los Angeles. Results clearly indicate that the sweeper can eliminate the dust plume during sweeping and give a cleaner street. However, additional research work is needed to refine the design and to demonstrate its capability in improving the ambient air quality. The following are recommended for further study:

1. Refine the design of the spray scrubber and incorporate it inside the hopper.
2. Improve the gutter broom sweeping efficiency for fine particles.
3. Demonstrate the sweeper on city streets and measure the improvement in ambient air quality.
4. Use a low pressure drop Venturi scrubber to clean the vent air instead of a charged spray scrubber.

Section 2

INTRODUCTION

URBAN FUGITIVE DUST EMISSIONS

Many metropolitan areas are out of compliance with the National Ambient Air Quality Standards for particulate matter largely because of urban fugitive dust emissions. A major urban fugitive dust problem is the dust emissions from paved roads. Draftz (1978) estimated that 40 to 70% of the total suspended particles in many urban areas comes from dust particles redispersed by road traffic. Pitt (1979) estimated that city streets can contribute from 5 to 50 $\mu g/m^3$ of particles to the urban air.

Table 1 shows the primary dust deposition and removal processes and rates for roads. Most of the dust deposition comes from mud and dirt carryout, such as from construction sites and heavy industrial traffic. Salting and sanding operations for ice control also can be a major source of dust. About one-half of the deposited dust may leave the street as particulate air pollution by either traffic related reentrainment or wind erosion.

Figure 1 further illustrates the street dirt loading rate for industrial, residential, and open roads. A street dirt loading of 50 g/curb-m or less is regarded as a clean street and a loading of more than 300 g/curb-m a dirty street. As can be seen, a street in an industrial area becomes dirty about two days after cleaning. Unless the street is cleaned, the dirt will be reentrained.

STREET SWEEPERS

Three basic street cleaning methods are currently in use:

TABLE 1. DUST DEPOSITION AND REMOVAL RATES FROM PAVED ROADS (AXETALL AND ZELL, 1977)

Deposition Process	Typical rate, kg/curb km-day	Removal Process	Typical Rate kg/curb km-day
Mud and dirt carryout	28.2	Reentrainment	28.2
		Displacement	11.3
Litter	11.3	Wind erosion	5.6
Biological	5.6	Rainfall runoff	14.1
Ice control compounds	5.6	Sweeping	9.9
Dustfall	2.8		
Pavement wear & decomposition	2.8		
Vehicle-related (incl. tire wear)	4.8		
Spills	<1		
Erosion from adjacent areas	5.6		

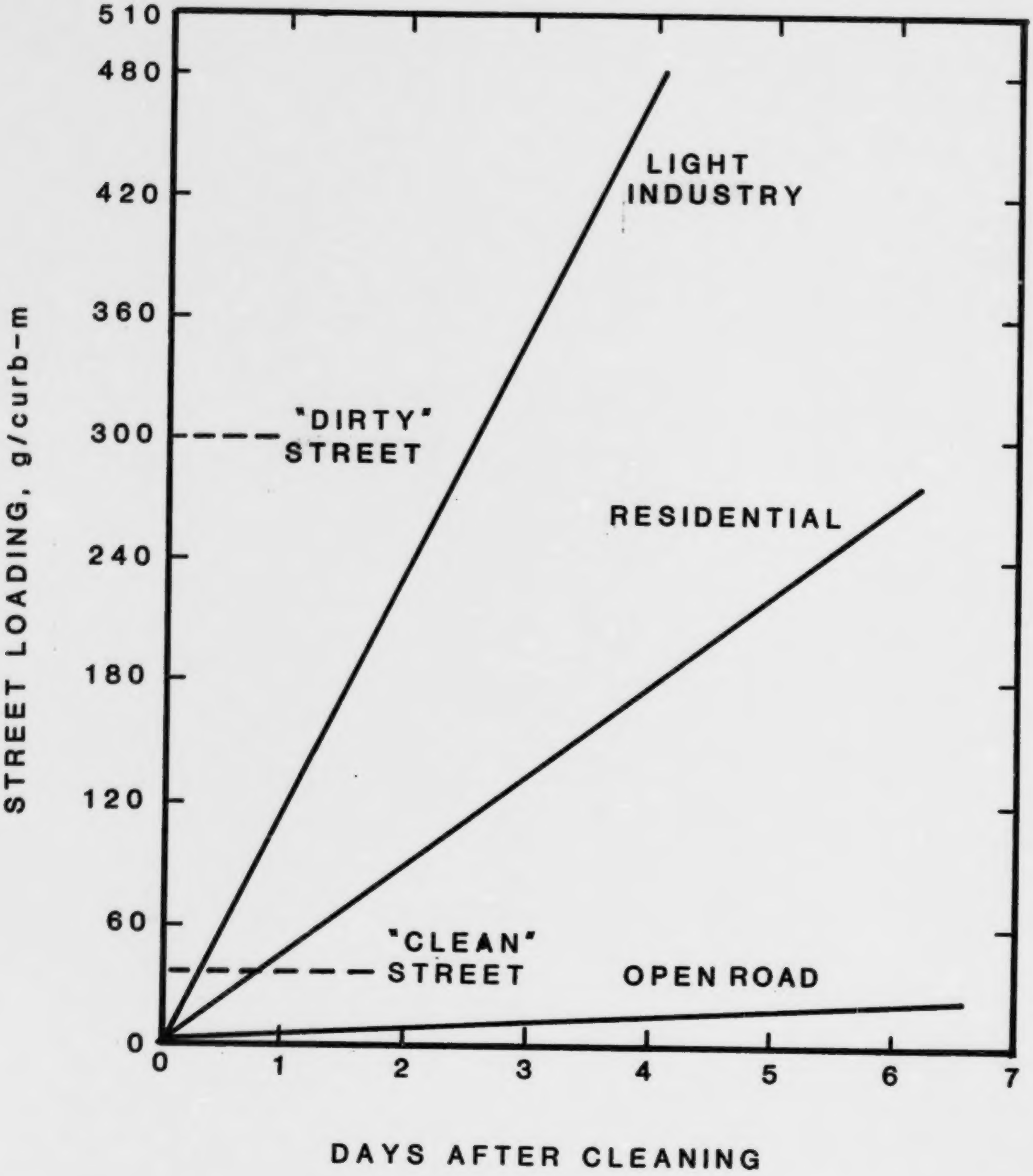


Figure 1. Street debris accumulation rates. (URS, 1974)

sweeping, flushing, and vacuuming. The existing types of street sweepers, which use the above cleaning methods, include broom, vacuum, regenerative vacuum, and water flushing sweepers. They generally have low-to-moderate efficiency for removing inhalable particulate matter (IPM) from streets and test data scatter widely.

Street sweepers and flushers are used in most urban areas. Traditionally, they have been designed for removing trash as well as dirt from roadways. Little effort has been directed at designing street cleaning equipment for collecting fine dust particles. As a result, conventional municipal street sweepers are not effective at removing inhalable particles from the street. This is illustrated in Table 2 which shows measured collection efficiencies from broom and vacuum sweepers as well as street flushers. None of these methods are consistently efficient for fine particle control. Sometimes more fine particles are left on the street after sweeping because large agglomerates are broken up by the sweeper.

Technology Needs

There are three major functions involved in any street sweeping system:

1. Dislodgement and containment of dust particles from the road surface.
2. Conveyance of dust particles to a dust collection hopper.
3. Prevention of fine particle emissions from the dislodgement apparatus, the hopper, and the conveying gas flow.

Existing sweeper systems need improvement in all three functions.

PROPOSED METHOD FOR SWEEPER IMPROVEMENT

The "Spray Charging and Trapping" (SCAT) system (Yung, et al., 1981) has been developed by A.P.T. under an earlier EPA contract as a control method for industrial fugitive emissions. The SCAT system uses air curtain and/or air jets to contain and

TABLE 2. CLEANING EFFICIENCY OF STREET CLEANING METHODS (Sartor et al., 1972)

Type of cleaning	Percent Removal of Material Particle diameter range, μm <44	 44-106	 106-841	 >841
Broom	-77*	-136	62	65
Broom	-11	- 15	11	45
Broom	1	34	52	30
Broom	63	80	62	1
Broom	8	24	23	28
Broom	9	40	52	78
Flush	-38	-13	3	- 2
Flush	90	90	-171	
Flush	29	25	7	-54
Flush	- 1	16	- 3	20
Flush	21	25	69	1
Vacuum	34	62	59	71
Vacuum	79	86	75	32
Vacuum	-85	2	60	73
Vacuum	-17	48	63	65

* Negative sign indicates an increase in particle mass in a given size range after sweeping.

convey fugitive particles to a spray scrubber which could be charged. This system also has the potential to greatly improve the performance of urban street cleaning equipment.

Figure 2 shows a schematic of the SCAT system applied to control urban fugitive dust emissions from paved roads. This system could be added to existing street cleaning equipment or could be incorporated in the design of new equipment. The unit operations involved are discussed below.

Dislodge Dust Particle

Brooms, brushes, scrapers, and other conventional devices are used to "sweep" the street. This dislodges dirt and fine dust particles from the roadway and sweeps them towards the dust pickup location. Many fine dust particles are redispersed into the air at this time.

It is expected that the brooms will adequately dislodge particles from the road surface; however, this may not be true with heavily loaded or muddy streets. To aid in dust dislodgement, high velocity air or water jets can be used.

Contain Dust

Redispersed dust particles must be contained and collected within the street sweeper system. The SCAT system uses air curtains to contain the dust within the sweeping system. Fine water sprays may be used to suppress, collect, and agglomerate redispersed dust. Either the drops or the particles (or both) may be electrostatically charged to increase the drop collection efficiency. Surfactants may also be added to the water to improve wetability of the dust particles.

Sprays may be injected into the sweeper air intake, into the hopper, into the exit duct from the hopper (sometimes a cyclone), and around the sweeper brooms at ground level. Water drops may be collected in an entrainment separator at the hopper exit, at the air intake, or by a squeegee liquid pickup device as in some small-scale commercial sweepers.

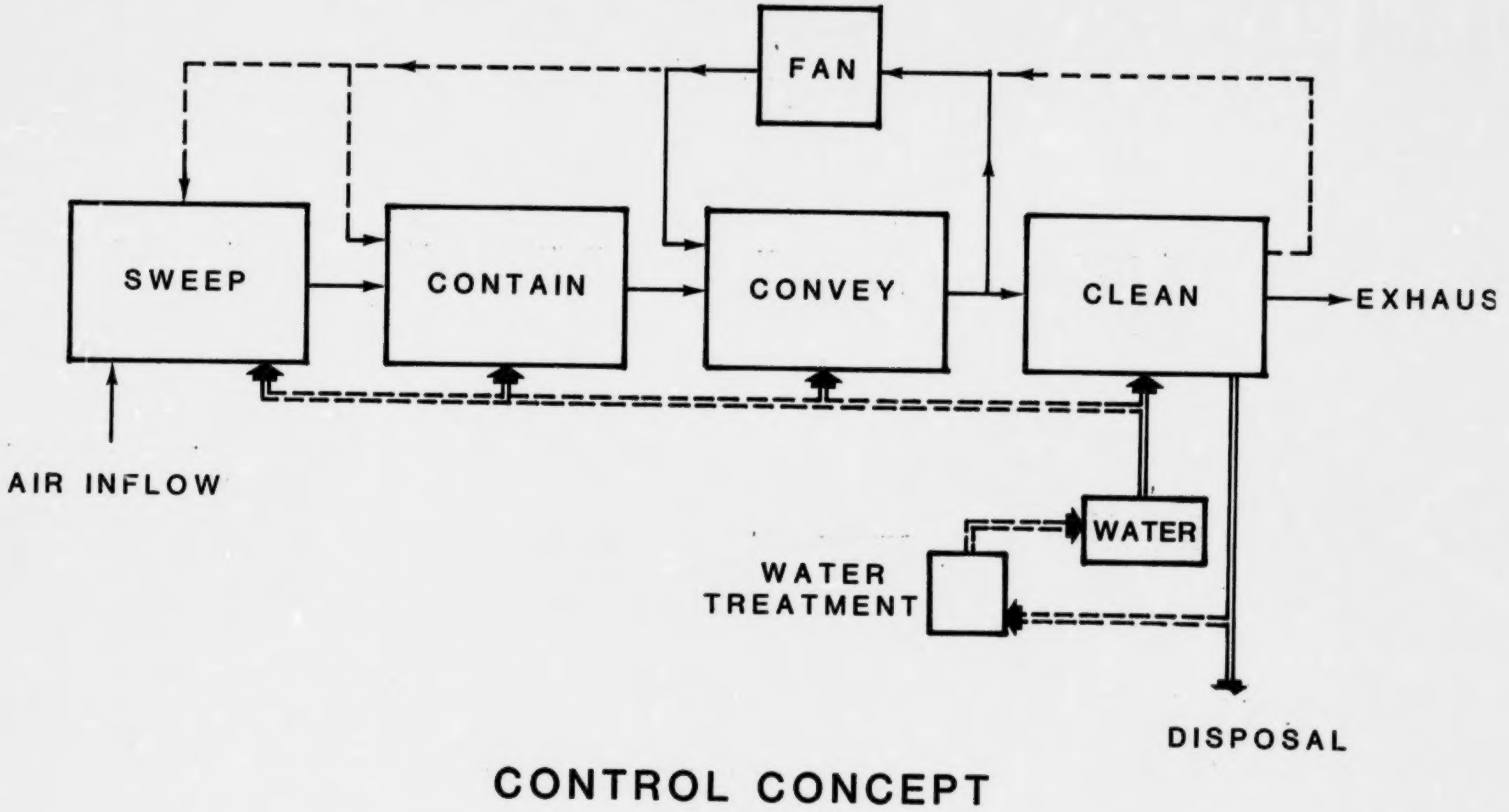

FAN
SWEEP
CONTAIN
CONVEY
CLEAN
EXHAUS
AIR INFLOW
WATER
WATER TREATMENT
DISPOSAL
CONTROL CONCEPT

Figure 2. SCAT system for controlling reentrained dust from paved roads.

Convey to Hopper

Once the dirt and dust are dislodged and contained within the street sweeper system, it is necessary to convey the dust and dirt to the hopper. The movement of the brooms and the use of scrapers convey a large amount of dirt and trash to the hopper. However, this is unlikely to be an effective method of conveying the inhalable dust which is suspended in the air. Very likely, it will be necessary to have an induced draft air flow into the hopper. This will aid in the containment and conveyance of redispersed dust.

Remove Dust From Air

At least a portion of the conveying air flow must be cleaned before being released from the hopper to the environment. Depending on the extent of agglomeration and collection of redispersed dust, it should be sufficient to use a good entrainment separator for final gas cleaning. Additional sprays may be necessary at the gas entrance to the entrainment separator in order to collect dust reentrained in the hopper.

An important option is to recycle a major fraction of the conveying air to the dust pickup point. There are many potential advantages to this option:

1. The recycle air may not need to be thoroughly cleaned because it is contained with the sweeper/SCAT system. Recycling fines may even increase fine particle agglomeration in the containment zone of the system.
2. The hopper sprays and entrainment separator will only handle a fraction of the total gas flow. This will minimize water and power requirements for final gas cleanup.
3. The recycle air will be moist, thereby minimizing evaporation of the water sprays and consequently reducing water consumption.

Water Treatment

To keep the system size and power requirements as small as possible, it is desirable to consider the need for, and economics of, water treatment and recycle. The water requirement is closely tied to the fraction of air which is recycled, the amount and size distribtion of inhalable particles which are redispersed, the extent of agglomeration of inhalable particles, the entrainment separator design, and the dust loading and size distribution in the gas which exits the hopper.

RESEARCH PROGRAM OUTLINE

Objectives

The primary objective of this research and development program was to develop practical means for improving the efficiency of a suitable street sweeper for the removal of IPM from urban streets. The applicability of the SCAT system was to be investigated.

Additional objectives of the program were to:

1. Build a modified street sweeper and demonstrate its capabilities for urban street sweeping.
2. Develop and use methods for evaluating sweeping efficiency.

Approach

The general approach of the program was consistent with the premise that a suitable scrubber could be designed if one knew what air flow rate and particle collection capability were required. In other words, much more was known about scrubber design than about street sweeping in terms of IPM control parameters. Consequently, the main effort was placed on determining:

1. Background information on street dirt and street sweeping. A literature search and interview of qualified persons were conducted to determine:
    a) The nature of dirt on paved roads, including information on the source of particulate matter, the methods of deposition, and various methods of removal.
    b) The prevalent types of street sweepers available, their operating principals, their costs, and the potential for improving them.
    c) Methods for sampling and analysis of the IPM on the street and in the air.
2. The street sweeper best suited for the proposed approach.
3. Design concepts for the modifications needed for IPM control. The following were considered:
    a) Develop possible approaches for improving performance and cost.
    b) Evaluate technical and economic feasibility through design studies.
    c) Select best alternatives for further evaluation.
    d) Identify areas where more information is needed.
4. A tentative set of design criteria to use for designing the experimental street sweeper, including:
    a) Air flow rates required to control dust emissions.
    b) The total air flow rate which has to be scrubbed.
    c) Particle size distribution and particle concentration in the uncontrolled effluent air.
    d) Utilities limitations.
5. Perform preliminary expeiments.
    a) Design experiments to provide necessary design information.
    b) Build apparatus
    c) Conduct experiments
    d) Evaluate results

6. Fabricate sweeper modifications.
    a) Functional equipment.
    b) Sampling and measurement apparatus.
7. Conduct performance tests.
    a) Develop test method.
    b) Perform tests.
    c) Analyze data.

A limited effort was expended on charged spray scrubbing and scrubber design. Some experimental work was done to confirm earlier experiments and to evaluate concepts for atomizers and drop chargers which could produce smaller charged drops than used in previous work. The further development of a mathematical model for particle collection by charged spray also received some effort.

Section 3

BACKGROUND INFORMATION

A literature search and interviews of qualified persons were conducted to determine:

1. The nature of dirt on paved streets, including information on the sources of particulate matter and the methods of deposition and removal of dust.
2. The prevalent types of street sweepers available, their cost, and the potential for improving them.
3. Methods for sampling and analysis of the IPM on the street and in the air.

STREET DUST LOADING AND SIZE DISTRIBUTION

Street dust loading is affected by many variables, such as meteorological conditions, vehicle traffic, roadway configuration, and pavement composition. The street dust accumulation rate can be obtained by performing a material balance on the street dust:

$$\begin{array}{l}\text{Accumulation Rate}\\ \text{of debris on the}\\ \text{street}\end{array} = \begin{array}{l}\text{Deposition Rate}\\ \text{of debris on the}\\ \text{street}\end{array} - \begin{array}{l}\text{Removal Rate}\\ \text{from the}\\ \text{street}\end{array} \qquad (1)$$

Figure 3 shows various processes for street dust deposition and removal (Axtell and Zell, 1977). The debris on the street could come from pavement wear, vehicle related deposition such as tire and brake lining wear, dust fall, litter, mud and dirt carryout, erosion spill, biological debris, and ice control compounds. The debris on the street may be removed by reentrainment, wind erosion, displacement, rainfall runoff, and street sweeping.

Vehicular mud and dirt carryover from unpaved areas, such as unpaved roads, parking lots, construction sites, and demolition

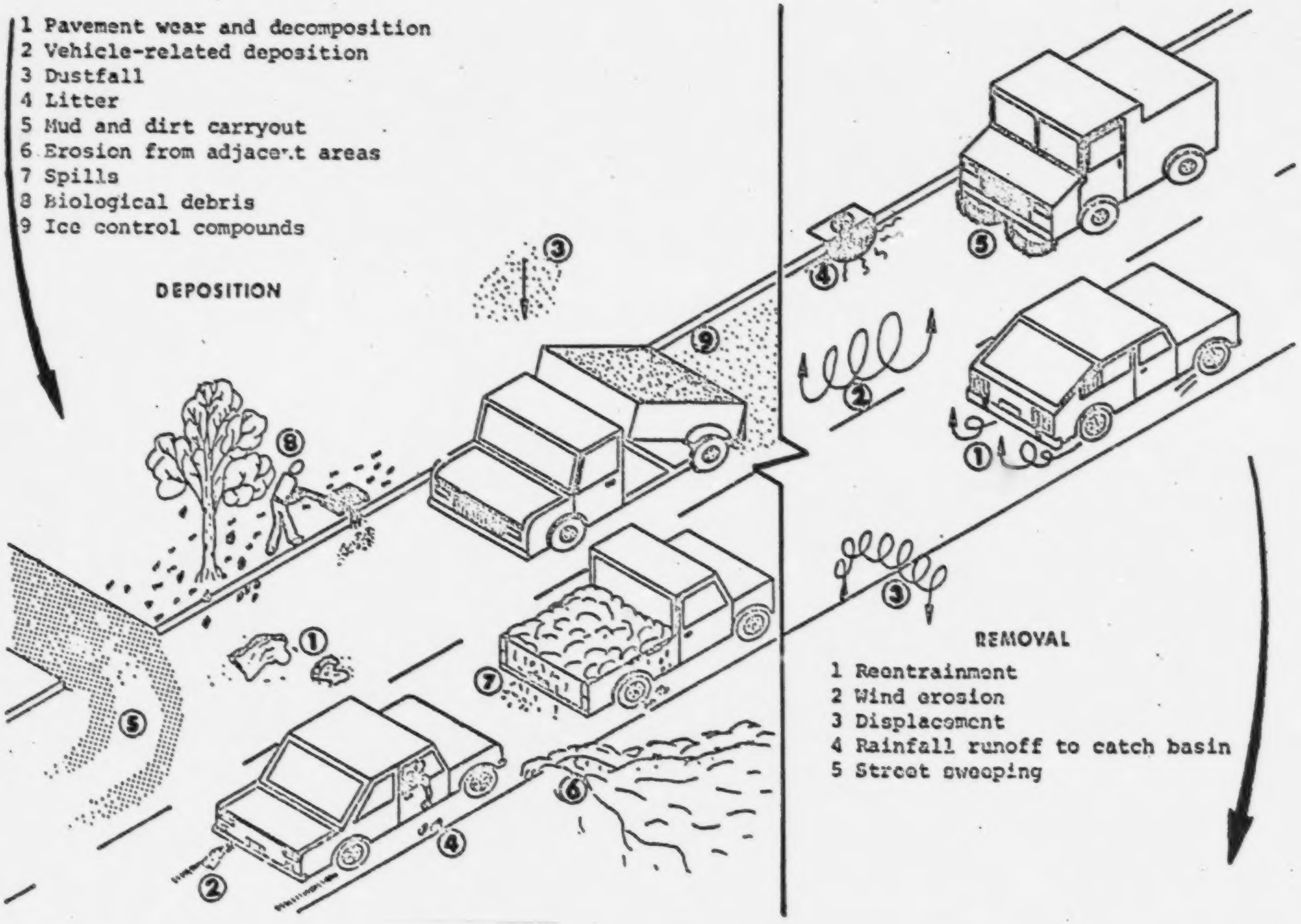

1 Pavement wear and decomposition
2 Vehicle-related deposition
3 Dustfall
4 Litter
5 Mud and dirt carryout
6 Erosion from adjacent areas
7 Spills
8 Biological debris
9 Ice control compounds
DEPOSITION
①
②
③
④
⑤
⑥
⑦
⑧
⑨
REMOVAL
1 Reentrainment
2 Wind erosion
3 Displacement
4 Rainfall runoff to catch basin
5 Street sweeping
①
②
③
④
⑤

Figure 3. Deposition and removal processes. (Axetell and Zell, 1977)

sites, is the major deposition process. Maximum carryover occurs in wet weather. According to Roberts et al. (1972, 1974), a car, driven at 16 km/hr (10 miles/hr) on a wet gravel road, collected approximately 3.6 kg of mud on tires and underbody, and carryover on tires from a wet unpaved parking lot averaged about 0.34 kg/vehicle.

Sartor and Boyd (1972) measured street dust surface loading and particle size distribution at sites in five cities. Their results are shown in Table 3. Dust loadings were found to depend on:

1. Time elapsed since the last street cleaning or rainfall.
2. Street surface characteristics: Asphalt streets had loadings that were 80% higher than concrete-surfaced streets, and streets in fair-to-poor condition had loadings about twice as high as streets in good to excellent condition.
3. Public works practices: Average loadings were reduced by regular street cleaning and increased during winter in areas where sand and salt were applied.

The major constituent of street dust was mineral-like matter similar to common sand and silt. Typically, 78% of the material was located within 15 cm from the curb and 85% within 30 cm from the curb.

It is anticipated that future emissions standards will be expressed in terms of inhalable particles which pose the primary threat to human health. Inhalable particles have been defined by EPA as those smaller than 15 μmA (in this report, the micrometer symbol "μmA" is used for aerodynamic micrometer).

The fraction of street dust which is in the inhalable size range was estimated from the data presented by Sartor and Boyd (1972) and is presented in Table 4. Approximately 0.5 to 2.5% of the total mass is inhalable.

Reentrainment and displacement due to vehicular motion and wind are the major removal processes and account for about 50% of the street dirt removal (Axetell and Zell, 1977). Both processes remove dust by resuspending the dust into the air. The

TABLE 3. STREET DUST SURFACE LOADING
(Sartor and Boyd, 1972)

Land Use	Mean Initial Accumulation Rate kg/km/day	Dust Loading (kg curb km)			
		Minimum	Maximum	Numerical Mean	Weighted Mean
Residential	105				339
Low/old/single		34	536	240	
Low/old/multi		9	367	251	
Med/new/single		51	339	121	
Med/old/single		73	536	-	
Med/old/multi		40	1,947	395	
Industrial	126				82
Light		73	3,386	734	
Medium		79	367	251	
Heavy		68	3,386	988	
Commercial	64				82
Central Business District		17	339	82	
Shopping Center		18	181	82	
Overall	98				423

Note: There are two curb-km per street-km.

TABLE 4. SIZE DISTRIBUTION OF STREET DIRT AND DUST (Sartor and Boyd, 1972)

PARTICLE DIAMETER	Milwaukee	Bucyrus	Baltimore	Atlanta	Tulsa
4,800 μm	12.0%	0	17.4%	0	0
2,000 - 4,800 μm	12.1%	10.1%	4.6%	14.8%	37.1%
840 - 2,000 μm	40.8	7.3	6.0	6.6	9.4
246 - 840 μm	20.4	20.9	22.3	30.9	16.7
104 - 246 μm	5.5	15.5	20.3	29.5	17.1
43 - 104 μm	1.3	20.3	11.5	10.1	12.1
30 - 43 μm	4.2	13.3	10.1	5.1	3.7
14 - 30 μm	2.0	7.9	4.4	1.8	3.0
4 - 14 μm	1.2	4.7	2.6	0.9	0.9
4 μm	0.5	0	0.9	0.3	0.1
MASS LOADING, kg/curb-km	761	389	291	121	93
% <15 μmA	1.2%	2.5%	2.4%	0.8%	0.5%
MASS <15 μmA ,* kg/curb-km	9.1	9.7	7.0	1.0	0.5

*for particle density of 2.5 g/cm^3

difference between the two is that in displacement the dust settles again nearby.

The accumulation of materials on the street has been found to level off within a period of three to ten days after a rainstorm or street cleaning (Sartor and Boyd, 1972). This leveling off occurs when traffic-related removal rates balance traffic-related deposition rates. The equilibrium is established more rapidly with increasing traffic speed.

Pitt (1978) determined the rate of the reentrainment from street surfaces by measuring the accumulation rate of dust on a thoroughly cleaned street. He then calculated the reentrainment rate by assuming that the reentrainment rate of debris from street is equal the removal rate of debris from streets and that the dirt deposition rate was constant. The amount of reentrainment increases with time as dirt deposits on the street (Figure 4).

Pitt (1978) calculated the emission rate of vehicles from equation (2) and his data and compared it with the data published in the literature.

$$\begin{array}{lcccc} \text{Reentrainment rate} & = & \begin{array}{c}\text{Emission rate of}\\ \text{Vehicles}\end{array} & \times & \begin{array}{c}\text{Frequency of}\\ \text{Vehicles}\end{array} \\ (\text{g/km-day}) & = & (\text{g/km-veh}) & \times & (\text{veh/day}) \end{array} \qquad (2)$$

Figure 5 and Table 5 show the results. Not surprisingly, the emission rates published in the literature vary considerably.

A number of studies have measured the size distribution of suspended particles in the vicinity of paved streets (Axetell and Zell, 1977; Cowherd et al., 1977; and Bohn et al., 1978). Figure 6 presents two suspended particle size distributions from the literature. Based on these size distributions, 90% removal of inhalable particles would require collecting all particles larger than about 1 to 4 μmA diameter.

The particle size distribution of dust emitted by the roads was also measured by Pitt (1978). He measured the concentration

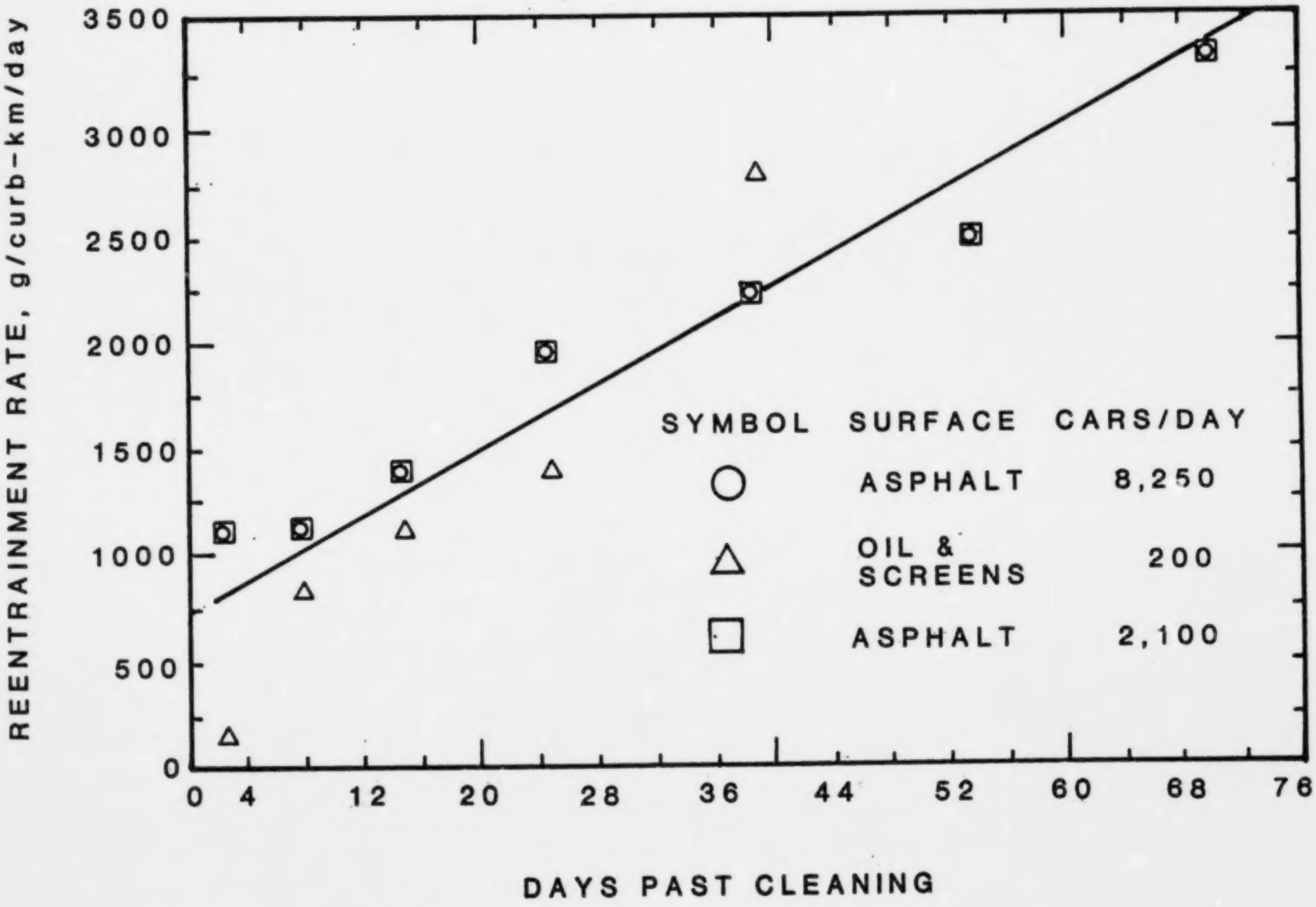


Figure 4. Rate of reentrainment of particulates from street surfaces (Pitt, 1979).

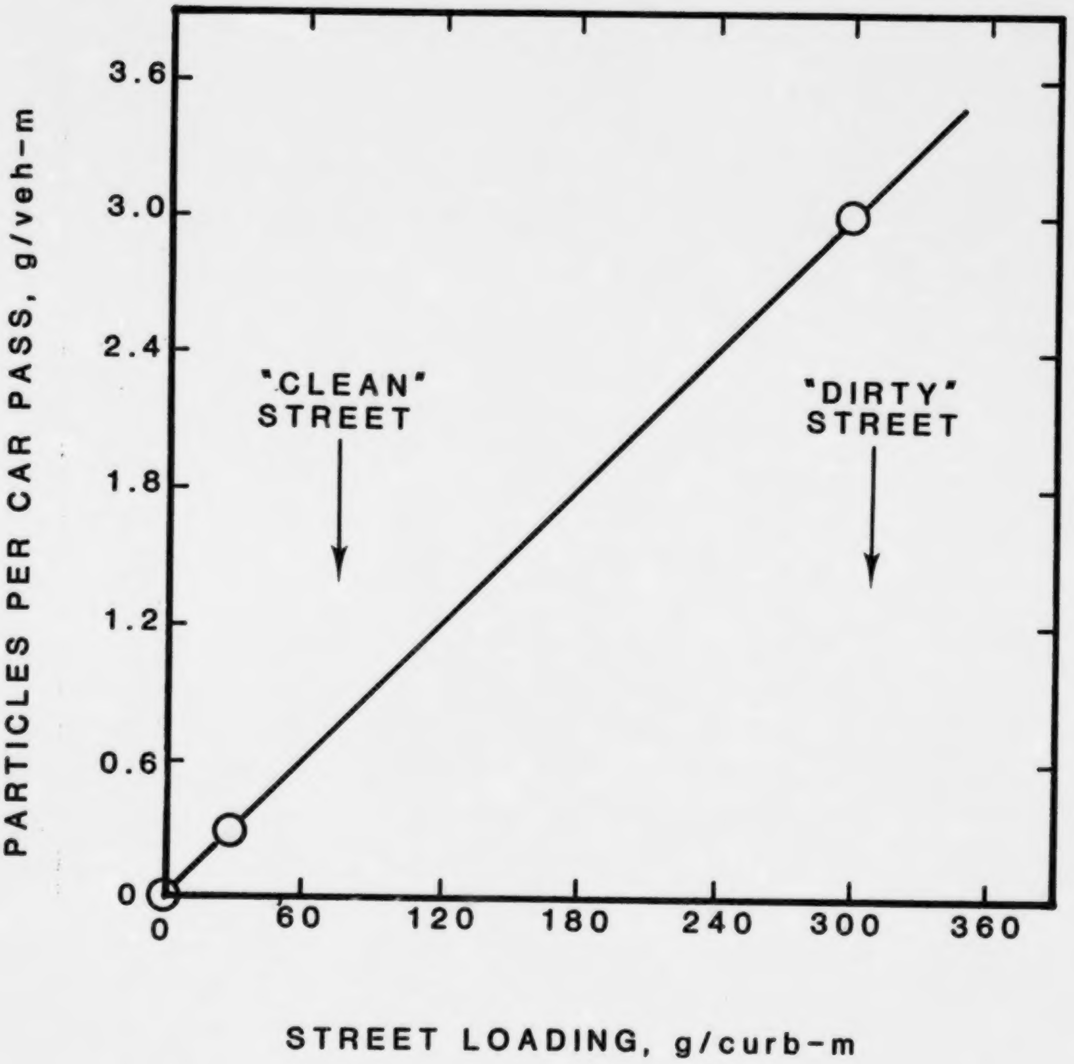


Figure 5. Reentrainment of dust by vehicles as a function of amount of street debris (Pitt, 1979).

TABLE 5. VEHICLE EMISSION RATES ON PAVED ROADS

Reference	Emission rate g/veh-km
Axetell and Zell (1977)	0.12 - 12.4
Cowherd et al. (1977)	8.1
Pitt (1978)	0.41 - 11.2
Sehmel (1973)	28

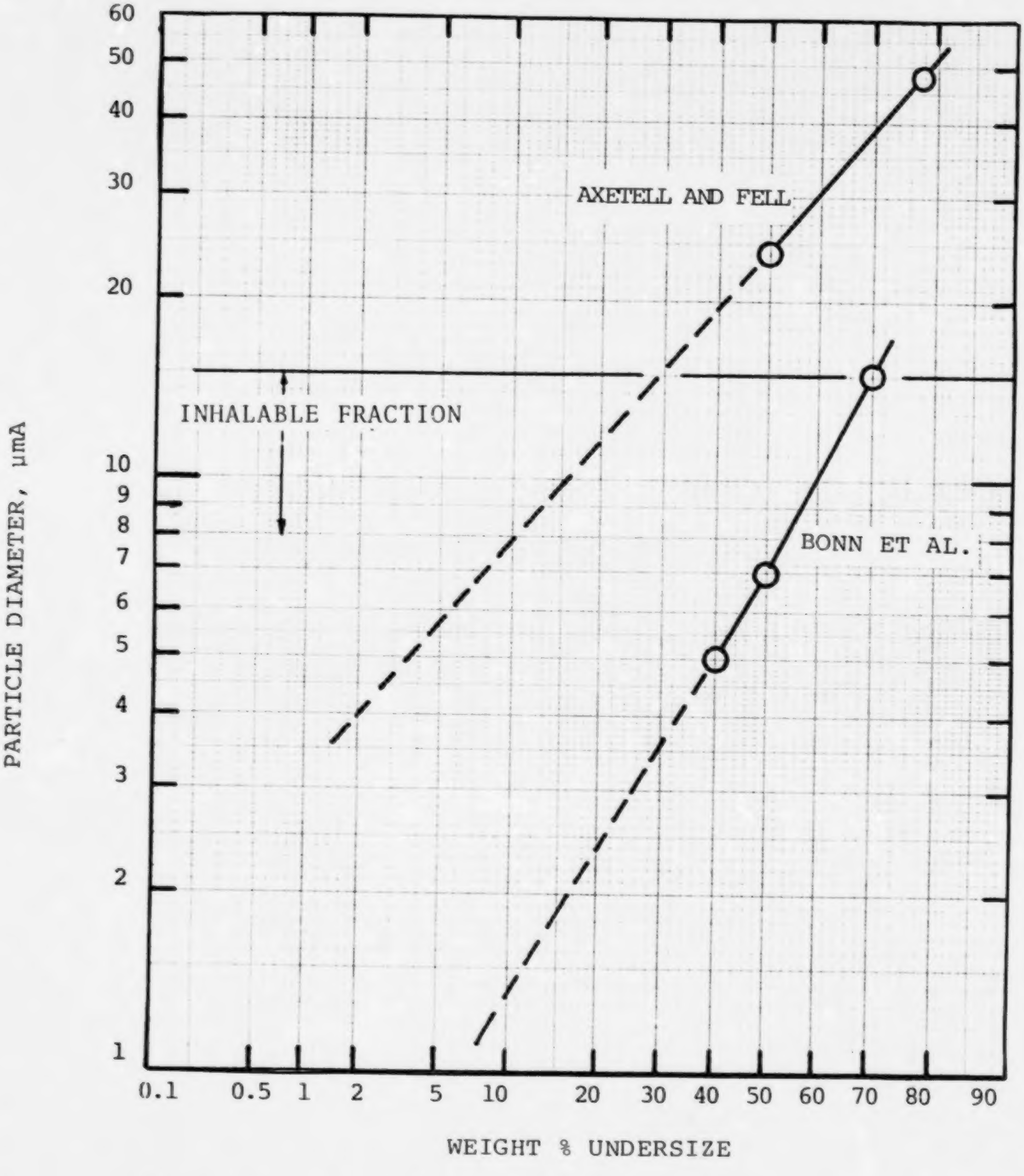


Figure 6. Size distribution of suspended dust in vicinity of paved streets.

of particles upwind and downwind of a road and calculated the difference. The size distribution (Figure 7) is not log normal and is widely variable. If a log normal approximation were made, the mean diameter based on the mass of particles would be approximately 10 μm. It should be noted that approximately 80% of the particles in the air are smaller than 30 μm diameter (Axetell and Zell, 1977). The road emission rate could not be calculated from their data because of unknown meteorological conditions.

Roadside Concentration of Particles

Some indication of the roadside concentration can be obtained from resuspension factors presented by Steward (1964) and Mishima (1964). The resuspension factor is defined as the ratio of airborne concentration (weight/volume) to the surface concentrations (weight/area). Values of the resuspension factors for vehicular traffic usually range from 10^{-7} to 10^{-5} /m. With a "clean" street surface (particulate loading of 30 g/curb meter, 100 lb/curb mile) the resulting roadside airborne particulate concentration from auto traffic may vary from 0.5 to 50 $\mu g/m^3$.

STREET SWEEPERS

Street sweepers and flushers are used in most urban areas. Traditionally, they have been designed for removing trash as well as dirt from roadways. Little effort has been directed at designing street cleaning equipment for collecting fine dust particles.

Street flushers flood the street with high velocity water sprays. This method can be effective in some applications, but generally it does not remove the inhalable size fraction effectively. Also, the water requirements and sewer capacity will limit the general application of this method.

Street sweepers can be sub-divided into 3 categories: mechanical, regenerative, and vacuum sweepers. Table 6 shows the

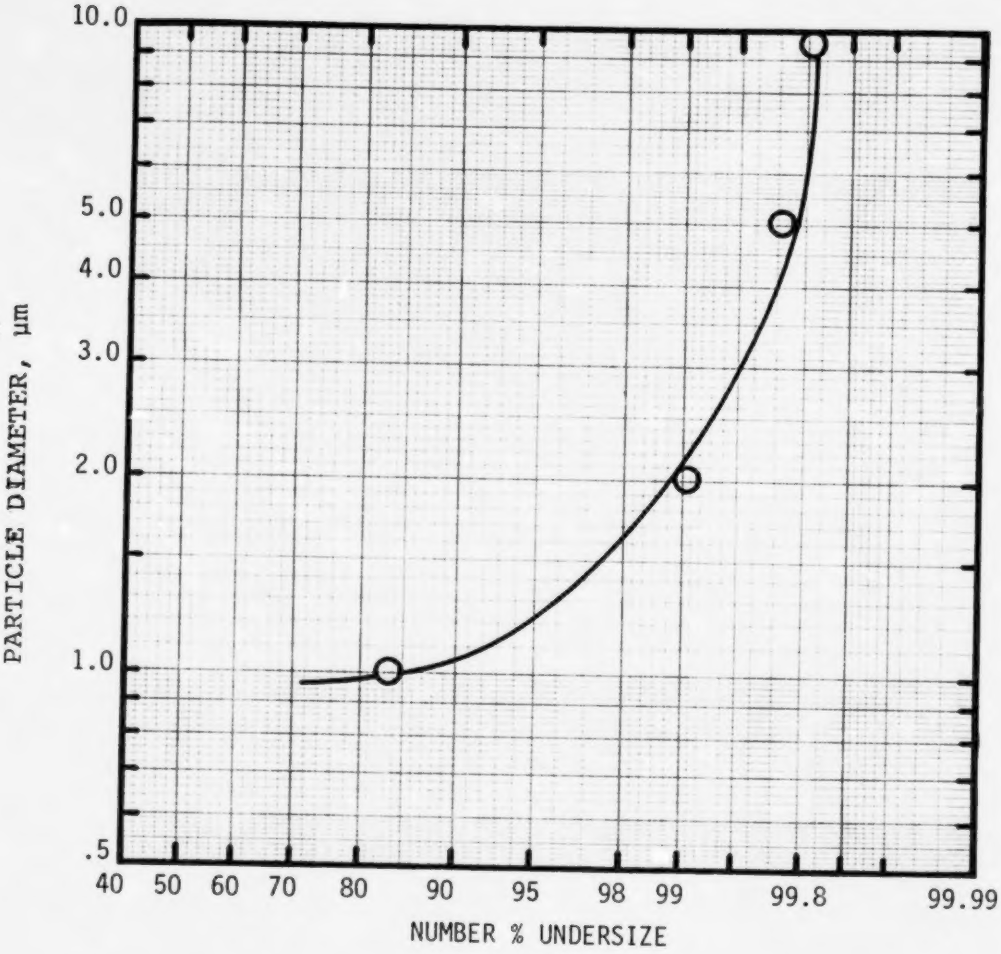


Figure 7. Particle size distribution near road (Pitt, 1978).

TABLE 6. TECHNICAL FEATURES ON STREET SWEEPERS

Function	Mechanical	Regenerative	Vacuum
Transfer of debris from gutter.	Gutter broom kicks dirt from the curb to the center plate. The sweeper moves forward and the debris comes into contact with pickup mechanism.	Same as mechanical sweeper.	Same as mechanical sweeper.
Main pick up.	The rear broom extends the entire width of the sweeper. It kicks the dirt to the conveyor/elevator belt.	The vacuum nozzle extends the entire width of the sweeper. The debris is stirred by an air jet and sucked into the hopper.	The vacuum nozzle is located on the right side of the sweeper and is about 3 ft. wide. A full width rear broom windrows the debris to the nozzle.
Transfer of debris to the hopper.	An elevator or conveyor belt	Transfer of air flow.	Same as regenerative sweeper.

TABLE 6 (continued). TECHNICAL FEATURES ON STREET SWEEPERS

Function	Mechanical	Regenerative	Vacuum
External dust control.	Water is sprayed on the street to wet the debris. Water is also sprayed on the gutter brooms and rear broom.	Water is sprayed on the street to wet the debris. Water is also sprayed on the gutter brooms, vacuum pickup head and in the dust hopper.	Same as regenerative sweeper.
Air clean up.	None.	The air velocity is decreased in the hopper to drop "large" particles. Water is sprayed on the dust in the hopper. The air is sucked into the fan through a centrifugal separator and expanded metal filter. The air is returned to the main pickup head.	Water is sprayed in the vacuum head. The air clean up is similar to the regenerative sweeper.
Water treatment.	The water is obtained from the fire hydrant and is disposed of in the wet debris.	Same as mechanical sweeper.	Same as mechanical sweeper.

TABLE 6 (continued). TECHNICAL FEATURES ON STREET SWEEPERS

Function	Mechanical	Regenerative	Vacuum
Maneuverability.	Three wheel sweepers are very effective in going around parked cars. Four wheel sweepers are not as effective as three wheelers but can travel at 55 mph. They are used by cities with large perimeters.	Available in four wheels only.	Available in four wheels only.
Possible modification to remove inhalable particulates.	Will require a new fan for fine dust pick up and cleaning.	Could use the existing fan for dust transfer pickup and cleaning.	Same as regenerative sweeper.

technical features on these three types of street sweepers. Table 7 shows information on commercially available sweepers.

A mechanical sweeper (Figure 8) uses a rotating gutter broom or brush to dislodge the dirt from the road and move it from the gutter area into the path of a large cylindrical broom which rotates to carry the dirt onto a conveyor belt and into the hopper. Water sprays are sometimes used to suppress the dust. This type of sweeper is available in several designs, including self-dumping and three- or four-wheel sweepers. Three-wheel sweepers are generally more maneuverable, but four-wheel sweepers can travel at higher speeds when not sweeping.

Vacuum assisted mechanical sweepers (Figure 9) use gutter and main pickup brooms for loosening and moving street dirt and debris into the path of a vacuum intake. A large volume of induced air flow sucks up the loosened particles and conveys them to the hopper. The debris are saturated with water on entry and settle out in the hopper. The air leaving the hopper passes through a coarse filter or screen which removes larger particles and protects the blower, and then is vented.

In regenerative sweepers, the loosened particles are blasted with air jets and sucked into the hopper. After cleaning with a cyclone, the air is recycled to the air jets.

DUST PICKUP MECHANISM

Information obtained from manufacturers indicates that mechanical broom sweepers represent about 85% of the municipal sweepers now in use. Street debris from the gutter is moved toward the center of the sweeper by the gutter broom. The rotating tips of the broom flick the debris toward the center where it hits the center plate. The big particles drop on the street while the small particles are dispersed in the air. The sweeper moves forward and the debris comes in contact with the rear broom. As the broom rotates and a fiber in the broom comes into contact with a particle of debris on the pavement, it must:

TABLE 7. INFORMATION ON STREET SWEEPERS

Model	Type Equipment	Cost 1979 $	Remarks
Elgin White Wing	Mechanical, 3 wheel, 1 gutter broom	$34,000	Has conveyor instead of elevator.
Elgin White Wing with hydrostatic drive	Mechanical, 3 wheel, 1 gutter broom	$40,000	The broom speed is independent of sweeper speed.
Elgin Whirlwind II	Vacuum, 1 gutter broom	$64,000	Good for cleaning downtown area.
TymCo 350	Regenerative air with 2 gutter brooms	$40,000	
FMC 3AH	Mechanical 3 wheel	$32,000	Hydraulic drive. Has some engine HP available.
FMC 993	Mechanical 3 wheel	$27,000	
Ecoloter Vacu-Sweep	Vacuum	$64,000	Available with diesel engines only.
Mobil TE-3	Mechanical 4 wheel	$44,800	With 1 auxiliary engine.

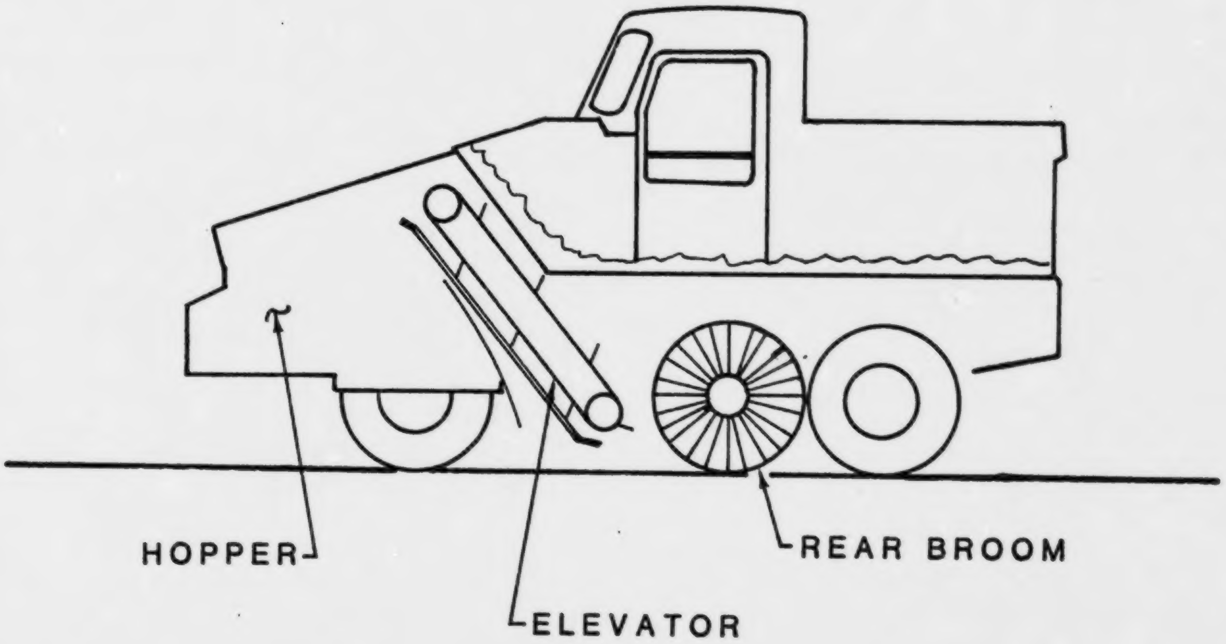
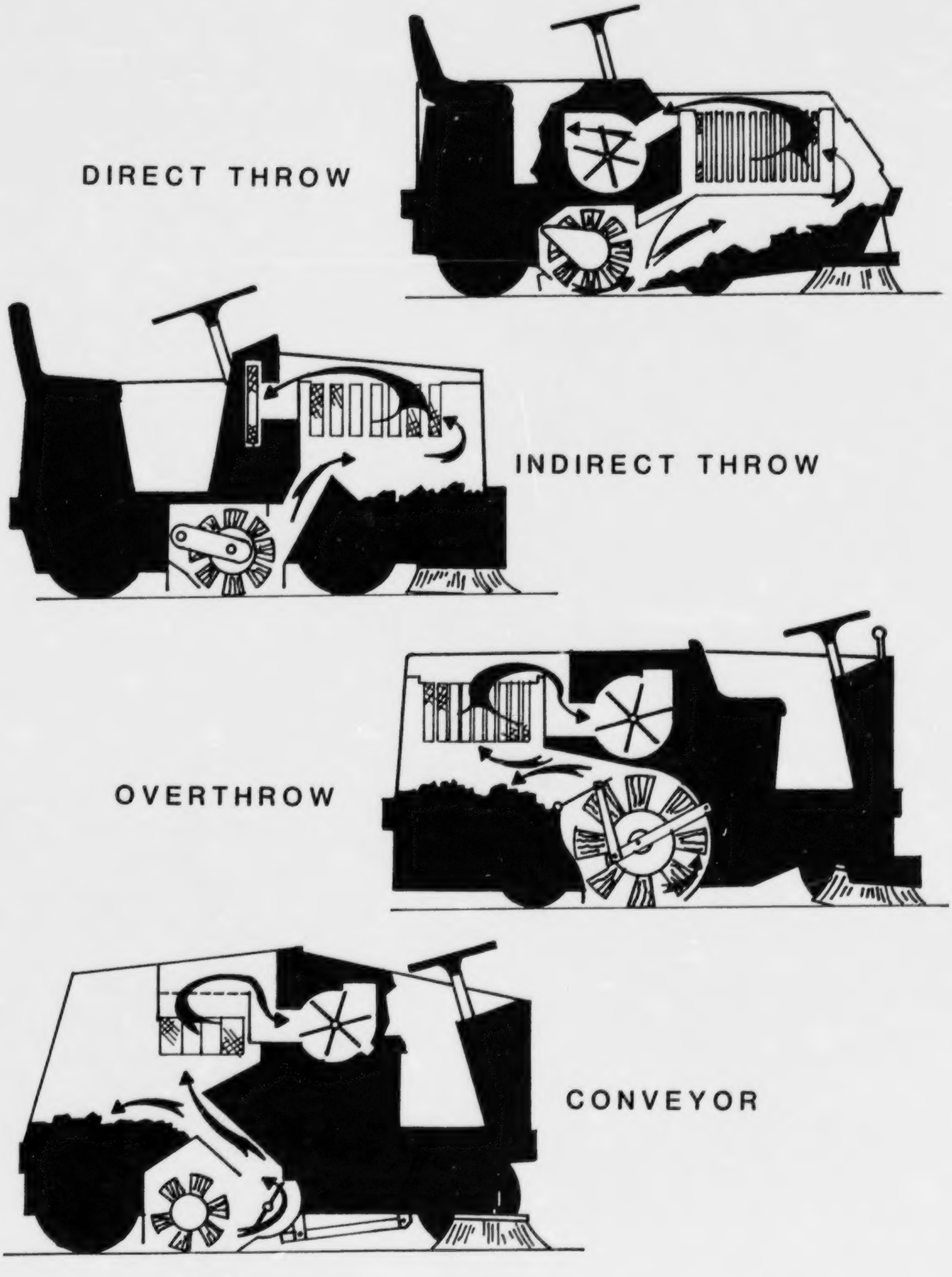

HOPPER
ELEVATOR
REAR BROOM

Figure 8. 3 WHEEL BROOM SWEEPER



DIRECT THROW

INDIRECT THROW

OVERTHROW

CONVEYOR

Figure 9. VACUUM ASSISTED SWEEPERS

1. Break the particles loose from the street surface and debris.
2. Transfer kinetic energy to the particle to move it from the street surface to the conveyor.
3. Direct the particle toward the elevator to avoid "spills" on the ground or in the air.

The variables affecting these mechanisms are:

1. Broom rpm.
2. Sweeper speed.
3. Broom material stiffness.
4. Sweeping pattern (width of rear broom touching the street, usually 15 cm).
5. Broom construction--spacing of fibers along the broom length.

Horton (1968) conducted a laboratory study to determine the effect of these parameters on the efficiency of a street sweeper. He found that the efficiency increases as broom rpm increases (Figure 10). The amount of debris increases as the sweeping pattern is increased (Figure 11). Limper broom materials like palmyra require larger patterns than stiff materials like wire brushes to obtain the same street cleaning efficiency (Figure 12).

STREET CLEANING EFFICIENCY

Street cleaning reduces the surface loading of dust and thereby decreases the reentrainment rate. The cleaning efficiency of a street sweeper depends on many conditions, such as the character of the street surface, street surface dust loading, particle size, and types of sweeper. Sartor and Boyd (1972) studied the effectiveness of a mechanical sweeper for various particle sizes and dust loadings. Pitt (1979) measured the performance of a mechanical sweeper and a vacuum assisted mechanical sweeper in different areas in the city of San Jose. Their results are shown in Tables 8 and 9. The conventional sweeper is effective in picking up litter larger than 0.63 cm

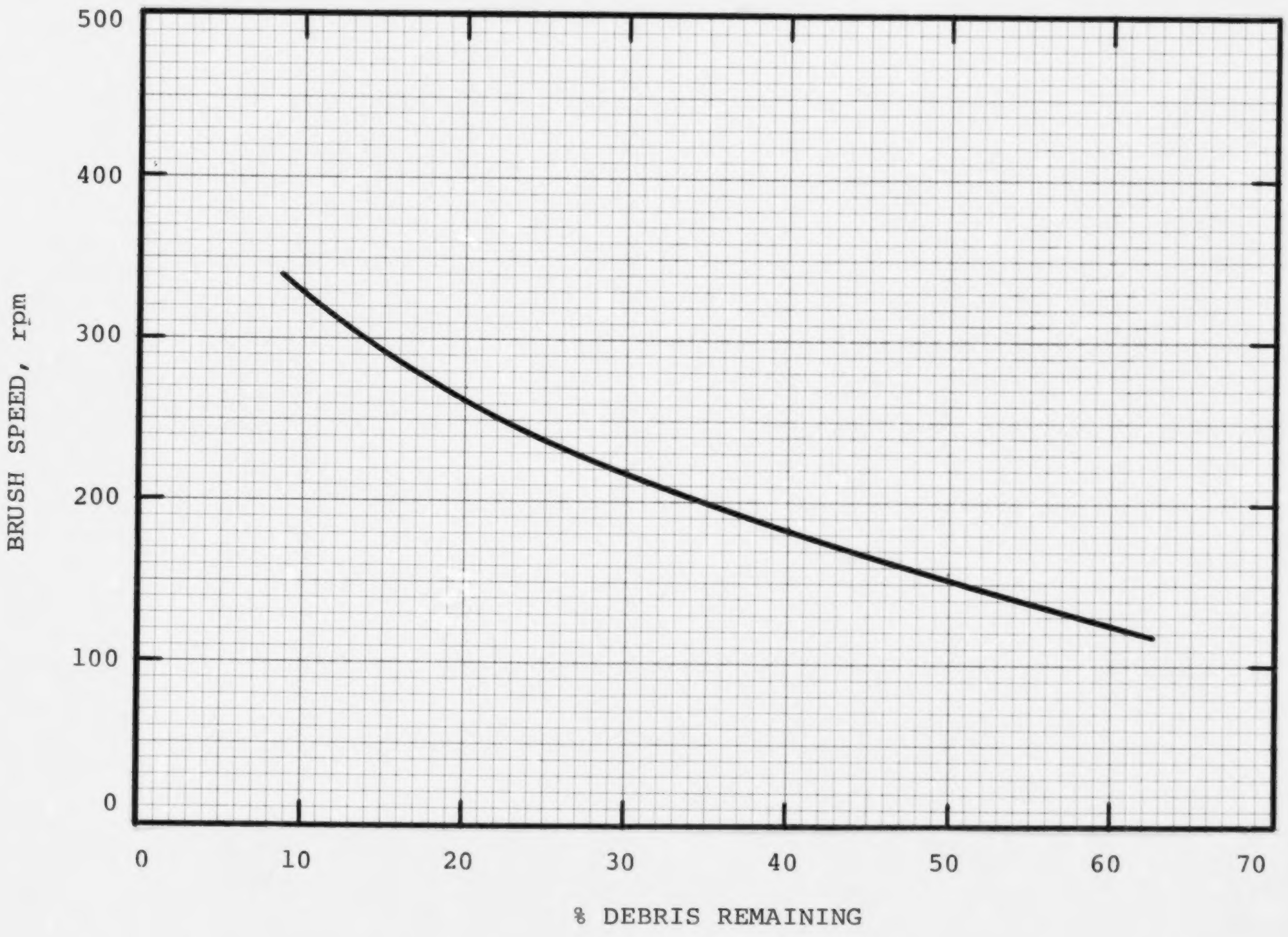


Figure 10. Debris picked-up versus brush speed (Horton, 1968).

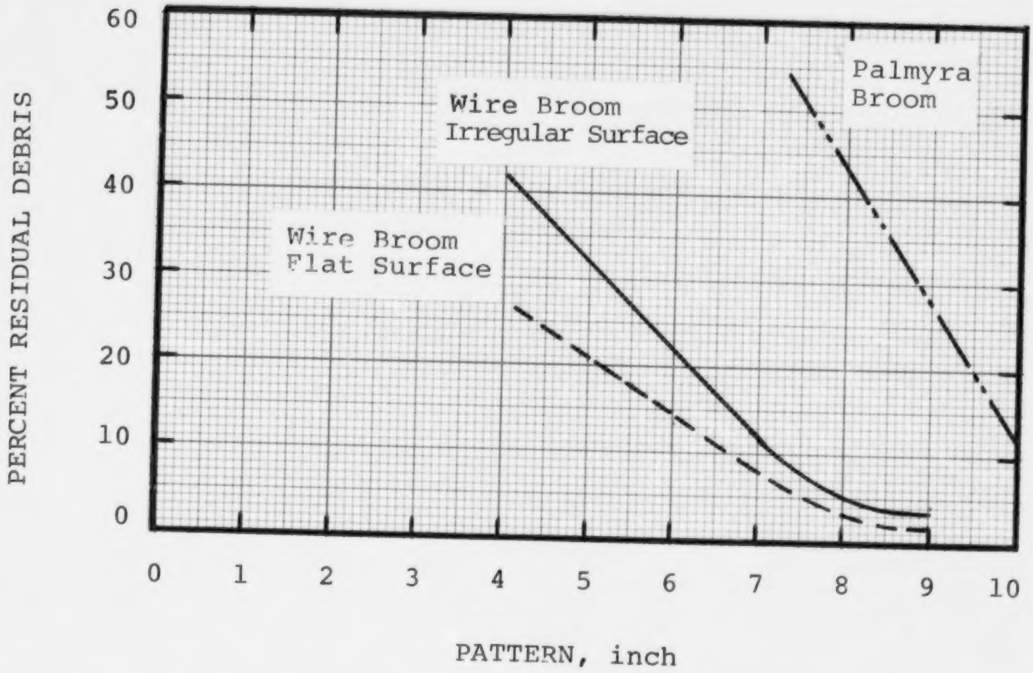


Figure 11. The effect of pattern on residual debris (Horton, 1968).

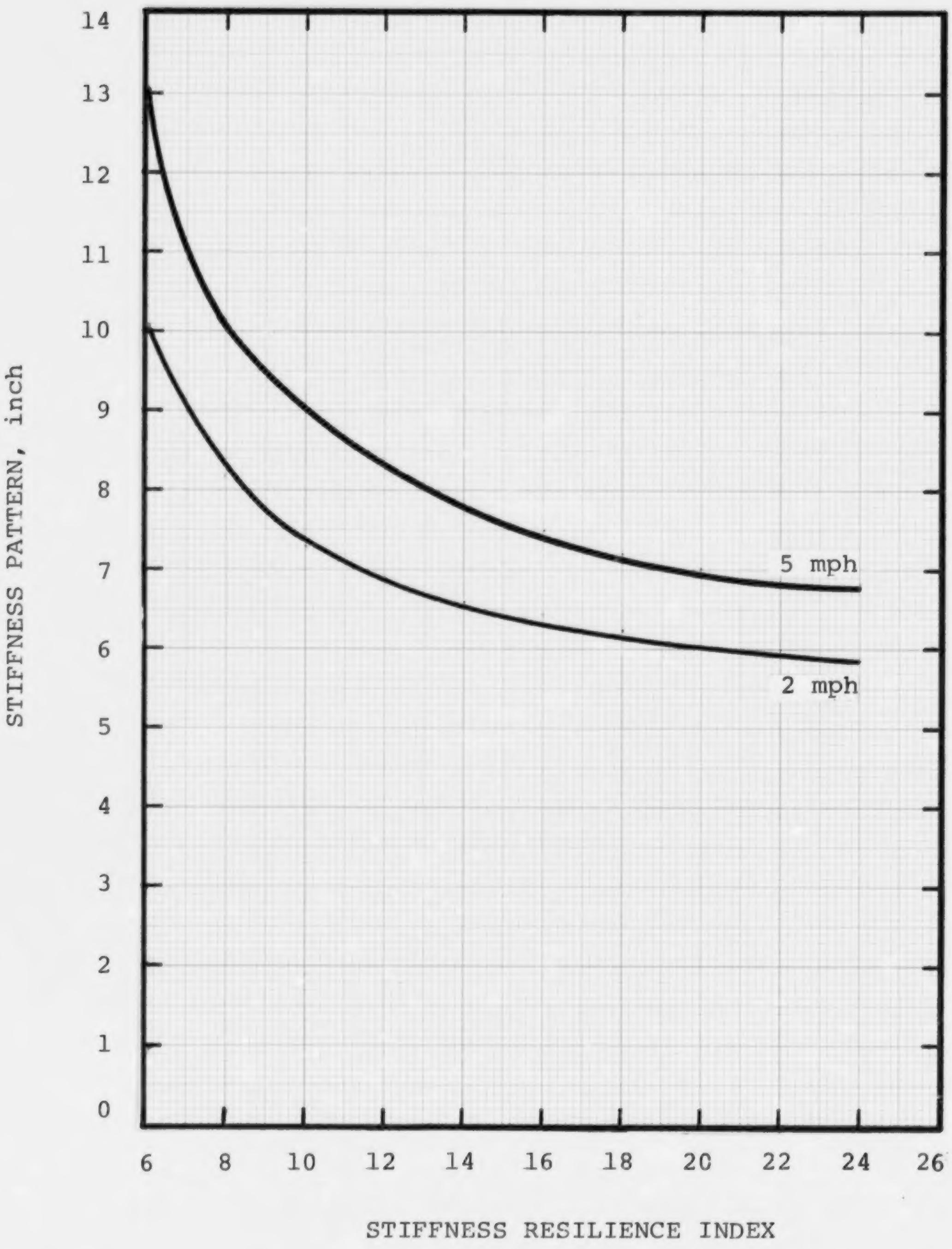


Figure 12. The sweeping pattern versus stiffners for synthetic broom fibers (Horton, 1968).

TABLE 8. SWEEPER EFFICIENCY WITH RESPECT TO PARTICLE SIZE (Sartor and Boyd, 1972)

Particle Size (μm)	Sweeper Efficiency, %
More than 2,000	79
840 - 2,000	66
246 - 840	60
104 - 246	48
43 - 104	20
Less than 43	15
Overall	50

TABLE 9. TOTAL SOLIDS STREET CLEANER REMOVAL EFFECTIVENESS BY PARTICLE SIZE (Pitt, 1979)

Study Area and Particle Size Range (µ)	Total Solids Initial Loading (lb/curb-mile)			Total Solids Removal ** (%)		
	Mean	Min.	Max.	Mean	Min.	Max.
Tropicana-Good Asphalt						
>6370	15	9.5	36	50	9	75
2000 - 6370	15	10	24	46	28	68
850 - 2000	21	13	42	47	22	74
600 - 850	15	8.2	42	53	41	79
250 - 600	42	19	81	46	14	63
106 - 50	50	22	80	41	6	58
45 - 106	51	24	70	40	21	54
<45	16	7.0	24	19	-54	64
all sizes	220	120	350	43	13	60
Keyes-Good Asphalt						
>6370	18	6.0	27	54	- 8	69
2000 - 6370	38	10	58	39	13	5
850 - 2000	54	16	87	35	8	5
600 - 850	28	9.2	44	35	12	5
250 - 600	85	39	120	31	14	4
106 - 250	83	45	100	26	11	4
45 - 106	76	34	100	23	-12	5
<45	21	13	34	8.3	-44	48
all sizes	400	170	550	31	14	47
Keyes-Oil and Screens						
>6370	73	13	120	36	20	58
2000 - 6370	270	77	450	24	- 5	47
850 - 2000	270	170	350	6.0	-16	23
600 - 850	160	100	200	4.0	-10	20
250 - 600	480	320	600	3.3	-16	18
106 - 250	380	280	540	4.0	-20	25
45 - 106	270	160	380	3.1	-30	25
<45	63	40	140	-12	-47	24
all sizes	2000	1200	2700	8.1	- 6	22
Downtown-Good Asphalt						
>6370	14	*	*	53	*	*
2000 - 6370	19	*	*	42	*	*
850 - 2000	25	*	*	39	*	*
600 - 850	14	*	*	38	*	*
250 - 600	48	*	*	36	*	*
106 - 250	56	*	*	33	*	*
45 - 106	57	*	*	22	*	*
<45	9.8	*	*	41	*	*
all sizes	240	*	*	34	*	*
Downtown-Poor Asphalt						
>6370	89	*	*	38	*	*
2000 - 6370	170	*	*	51	*	*
850 - 2000	180	*	*	42	*	*
600 - 850	85	*	*	41	*	*
250 - 600	270	*	*	42	*	*
106 - 250	270	*	*	39	*	*
45 - 106	230	*	*	33	*	*
<45	58	*	*	28	*	*
all sizes	1400	*	*	40	*	*

*Not enough samples were collected to obtain meaningful loading ranges.

**Sweepers were 4-wheel mechanical and 4-wheel vacuum assisted mechanical sweepers.

(0.25 in) diameter. However, its efficiency drops sharply as particle diameter decreases.

STREET DUST SAMPLING

To determine the reentrainment rate or the street sweeper sweeping efficiency, the street surface dust loading needs to be measured. Sartor and Boyd (1972) measured the street dust loading by sweeping and water-flushing the sample area. Cowherd et al. (1977) and Pitt (1979) used vacuum cleaners to suck up the dust from the road surface. Pitt (1979) claims that dry vacuum sampling is capable of removing 99% of the particles from the street surface.

Section 4

PRELIMINARY EXPERIMENTS

Dust is dispersed by the gutter broom and the pickup nozzle head of the sweeper during sweeping operations. Particle size distribution of the dust is an important variable required to design the SCAT system, and is a function of several factors; amount of dirt on the road, size distribution of dust on the road, type of road surface, moisture content of the dirt and vehicle operating conditions. Very little information is available in the literature on the dust dispersion mechanisms and the size distribution of the redispersed dust.

To obtain design information for the spray scrubber, the particle size distribution and concentration of the street dirt redispersed by the street sweeper brooms was experimentally determined. The following sections presents the results on dust dispersement.

AIR FLOW NEAR BROOM

Mechanical broom sweepers represent approximately 85% of the municipal sweepers now in use. Approximately 65% are 3-wheel designs and 20% are 4-wheel. For this reason, the initial decision was to modify a mechanical sweeper and the first series of experiments were done on a 4-wheel mechanical sweeper (Mobil model M6).

Street debris from the gutter is moved toward the center of the sweeper by the gutter broom. The rotating tips of the broom flick the large particles toward the center and the small particles are dispersed in the air flow near the broom. The air flow is due to:

1. Broom rotation
2. Sweeper motion
3. Wind

The air flow near the gutter and rear broom was measured with a hot wire anemometer on a stationary 4-wheel mechanical sweeper and is presented in Figure 13. The wind velocity was negligible. The air velocity at the broom surface is almost equal to the tip speed of the fibers. The velocity decreases steadily away from the broom. The velocity decreases to 10% of the maximum within 15 cm from the broom. The gutter broom is inclined at 10° to the horizontal to obtain a "strike" pattern on the curb. Near the edge above the ground the air velocity decreases to 10% of the maximum within 30 cm away from the broom.

REDISPERSED STREET DUST CONCENTRATION AND SIZE DISTRIBUTION

The mass concentration and size distribution of dust redispersed by the street sweeper were determined with cascade impactors and filters. The ambient air was sampled by cascade impactors located at the curb before and during the sweeper passed by. Three nucleopore filters were clamped under the sweeper between the gutter broom and the rear broom. After sampling, the filters were washed and the particles were analyzed by a Coulter counter.

The results from the Coulter counter analyses of the three filters are presented in Figure 14 along with that reported by Pitt (1978). The mass median diameter of dispersed dust measured by A.P.T. ranged from 2.5 to 3 μm physical diameter. Only 5 to 10% of the dust is smaller than 1 μm. No particles larger than 10 μm were redispersed and collected on the filters. The three filters collected a total of 7.0 mg which corresponds to an average dust concentration of 313 mg/m^3.

The cascade impactors collected insignificant amounts of dust. This was a result of the short sampling time and windy conditions.

The experiment was designed to obtain information on the mass and size of particulate which are redispersed from the road through the actions of the sweeper brooms. The loading of dirt

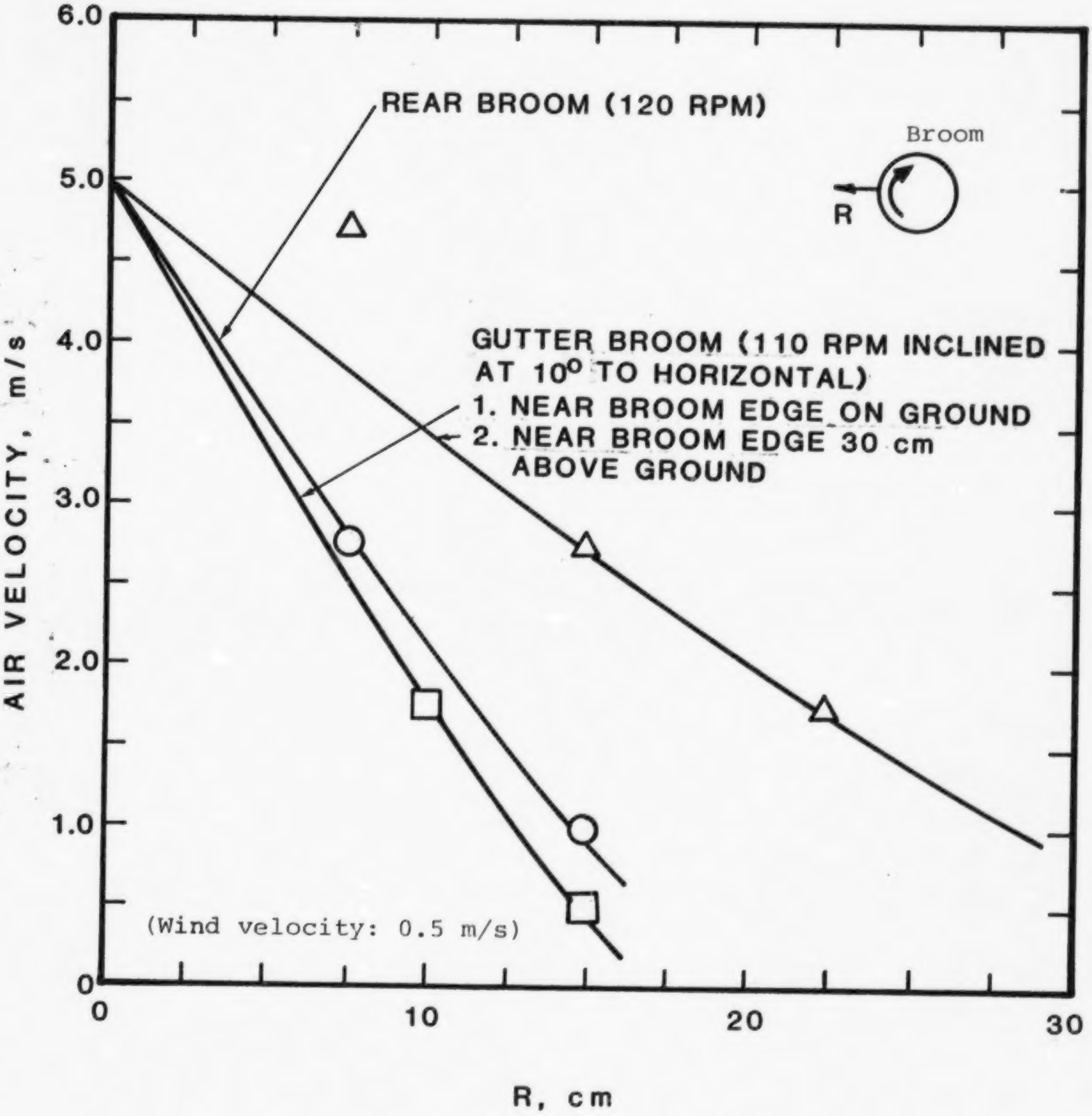


Figure 13. Air velocity near brooms of a Mobil M6 sweeper.

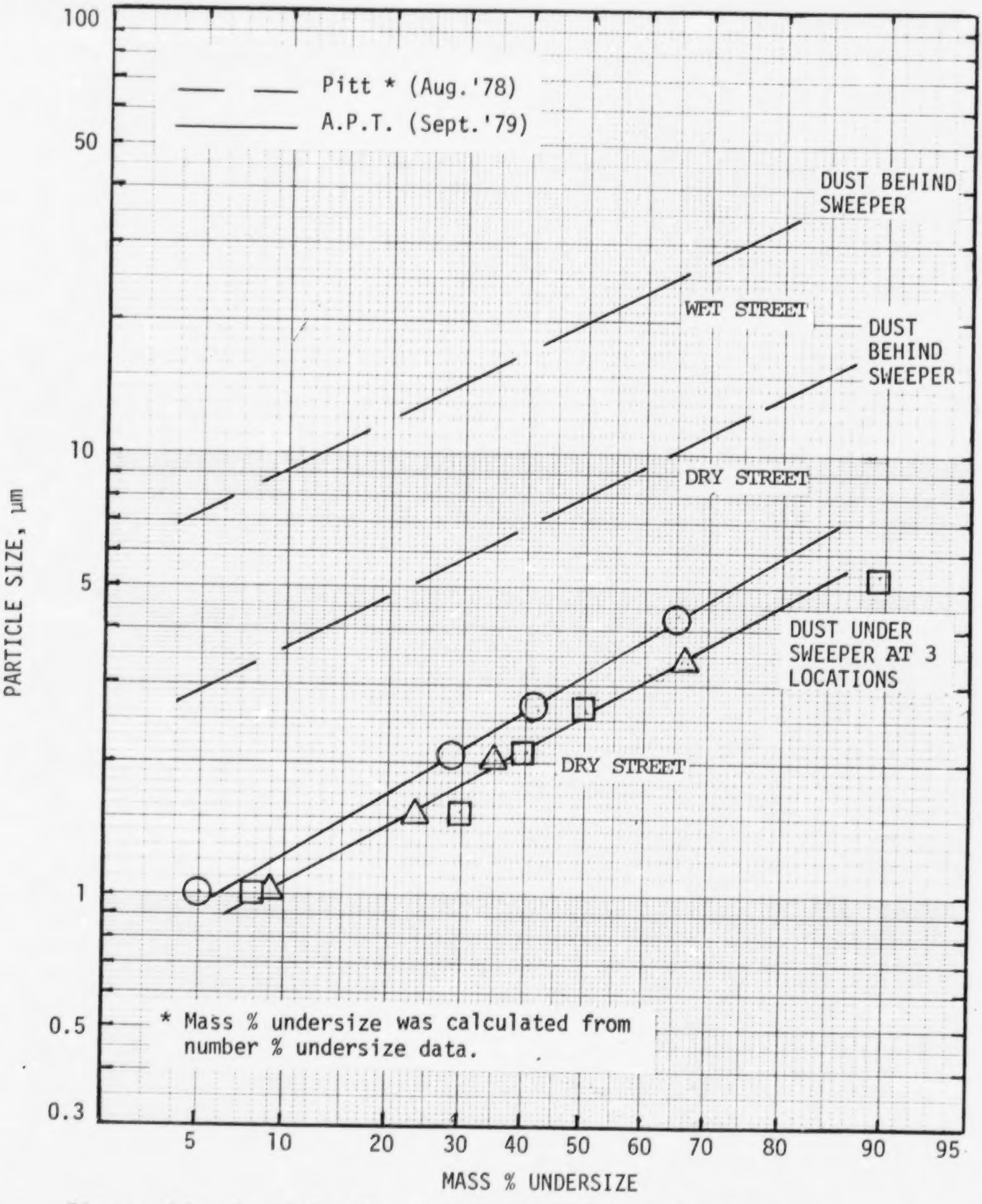


Figure 14. Particle size distribution of dust dispersed by a mechanical street sweeper.

on the street was not measured and no data were available to correlate the degree of dispersement by the broom.

Photographs of the dust cloud around the gutter broom, under the sweeper, and behind the rear broom were taken to show their location. Visually, the sweeper brooms appear to be very good at redispersing the fine dust particles. Some dusty air was observed to seep into the driver cab. The street side gutter broom spreads the dirt towards the center of the road surface after a sweeper pass.

Buchwald (1967) reported an average concentration of 2×10^8 particles/m^3 ($d_p < 5\mu m$) in the sweeper cab for an "average" street sweeping condition. The cab was partially enclosed and the dust seeped through the cracks. The particle concentration under the sweeper in this experiment was 2.8×10^{10} particles/m^3. The sweeper did not use water sprays to suppress the dust in this experiment.

Pitt (1978) reported data on the size distribution of dust dispersed behind a broom sweeper. His results are plotted in Figure 14. He found that the mean particle size increased when the operator swept on wet ground.

The redispersed dust measured by Pitt (1978) was larger in diameter than that measured in the present study. A Coulter counter was used to analyze the particles collected on the filter in this study. Agglomerates of dust particles in the air may have broken down to primary particles during Coulter counter analysis. Thus, the actual mean particle diameter may be larger than that shown. Differences in sampling location, street surface, dust concentration on street may also have contributed to the difference in measured size.

To determine the size distribution of dust dispersed by the sweeper as it exists in the air, the sampling system shown in Figure 15 was built. The system consisted of a pre-cutter to remove large particles, a cascade impactor (University of Washington, Mark III) a rotameter, and a portable vacuum pump. The sample flow rate was measured by the rotameter and was checked against that calculated from the pressure drop across the

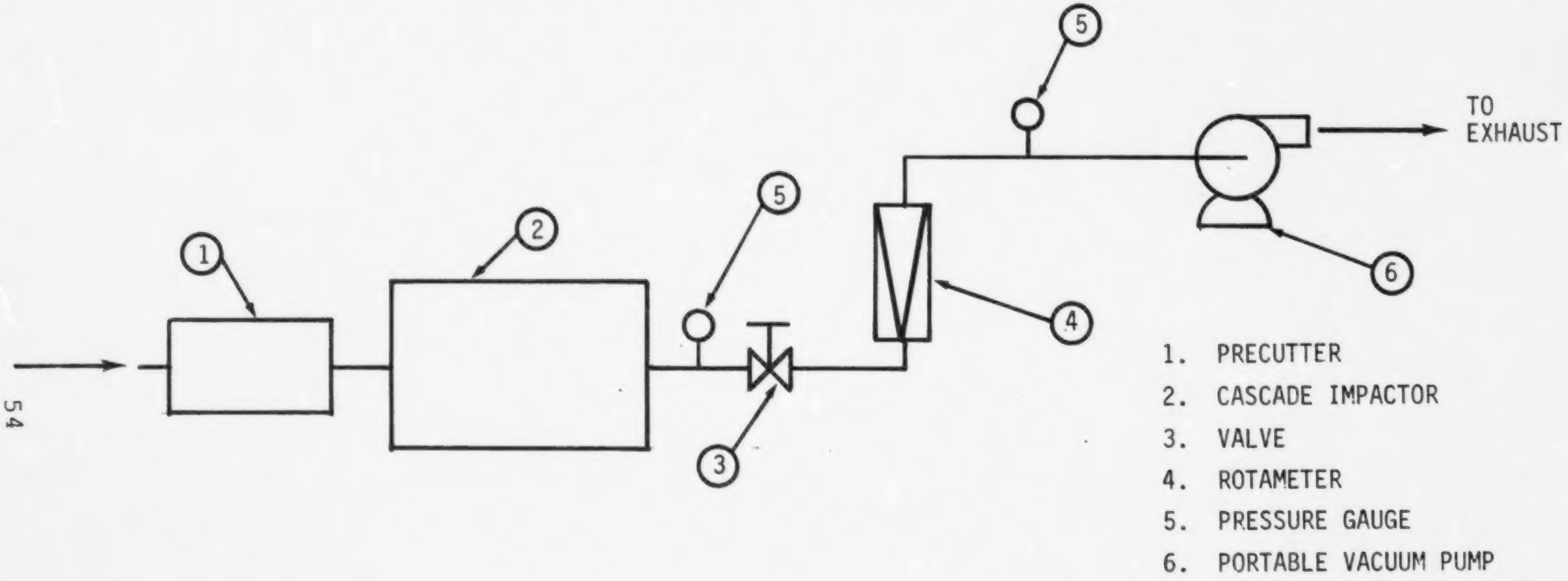

1
2
5
3
4
5
6
TO EXHAUST
1. PRECUTTER
2. CASCADE IMPACTOR
3. VALVE
4. ROTAMETER
5. PRESSURE GAUGE
6. PORTABLE VACUUM PUMP

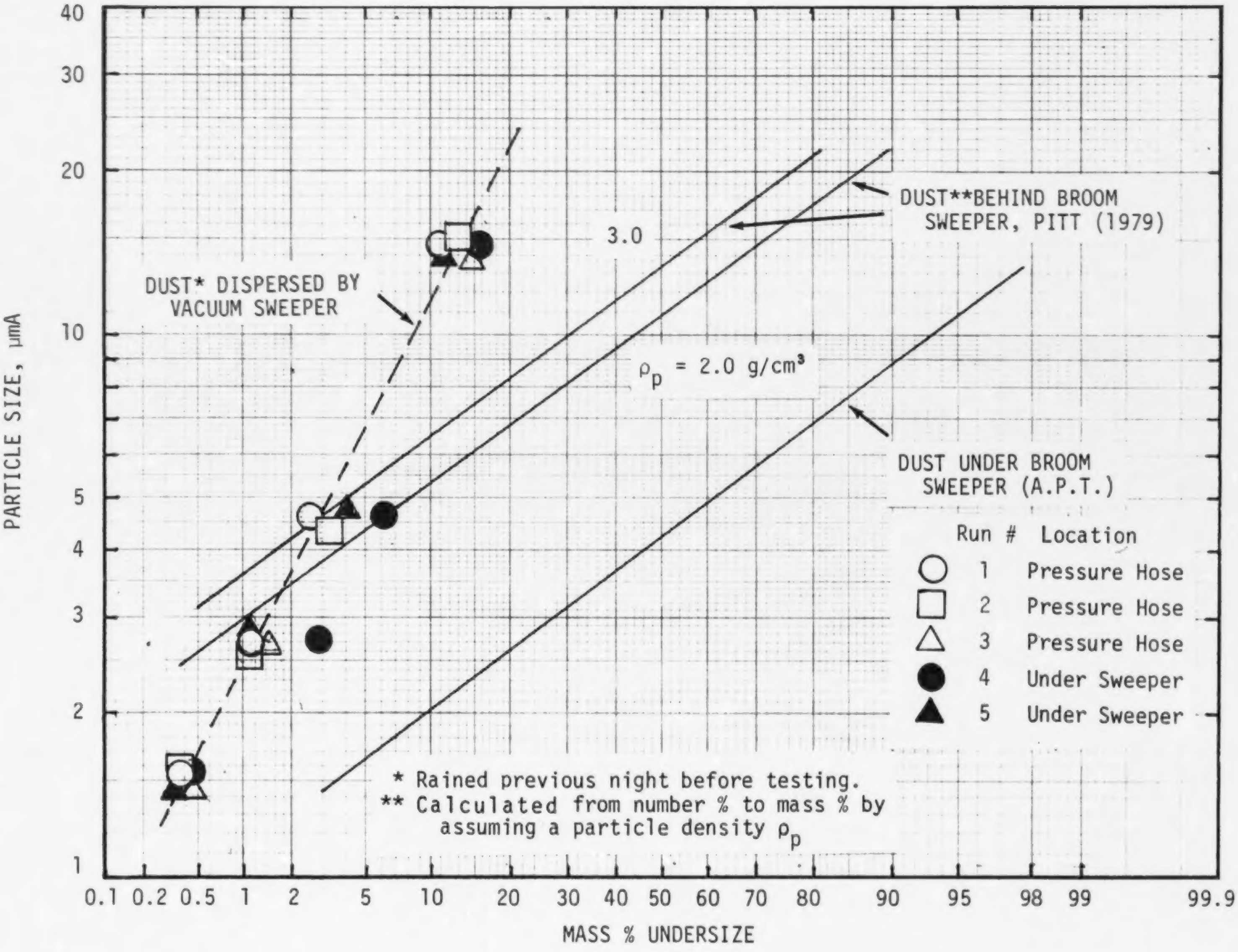
Figure 15. Schematic diagram of sampling equipment for particle size distribution data.

impactor. The pump power came from a storage battery.

The sampling system was calibrated and tested on the Mobil broom sweeper. However, before sampling was scheduled to start, word was received from EPA that they would prefer to modify a vacuum sweeper because more and more municipalities were switching to this type of sweeper. For this reason, no additional sampling was done on the Mobil sweeper. Instead, sampling was done on a Tymco Model 600 regenerative vacuum sweeper owned by the City of Anaheim, California (descriptions of the Tymco sweeper are presented in the next section).

Air samples were taken near the gutter broom and from the pressure hose of the Tymco street sweeper. One cascade impactor was mounted on the centerplate of the sweeper for sampling in the gutter broom area. Another cascade impactor was mounted on a plate covering the porthole on the pressure hose and a sampling nozzle was inserted in the hose to draw air samples. A light industrial area was chosen for field testing. The dust was not suppressed by water sprays. The sweeper travelled at approximately 9 km/hr (5 miles/hr) on the street. The sampling was conducted on a sunny day, but it had rained on the evening before the test. The average density of the street dust was determined in the laboratory with a pyncometer to be 2.46 g/cm^3.

Dust was sampled for 15 minutes in the gutter broom area, and for 5 minutes in the pressure hose. The particle size distribution of dust sampled are plotted in Figure 16. The cumulative mass concentration data are plotted in Figure 17. The data are compared with previous tests and data reported by Pitt (1979), who measured the particle size distribution with a particle counter. His data are converted from number percent to mass percent by assuming a density of 2 and 3 g/cm^3 for the street dust. A wide range of values of mean particle sizes and cumulative mass concentrations of dust dispersed by street sweepers have been measured. The differences are mainly due to variations in the following three parameters:



* Rained previous night before testing.
** Calculated from number % to mass % by assuming a particle density ρ_p

Figure 16. Particle size distribution of dust dispersed by a vacuum (regenerative air) sweeper.

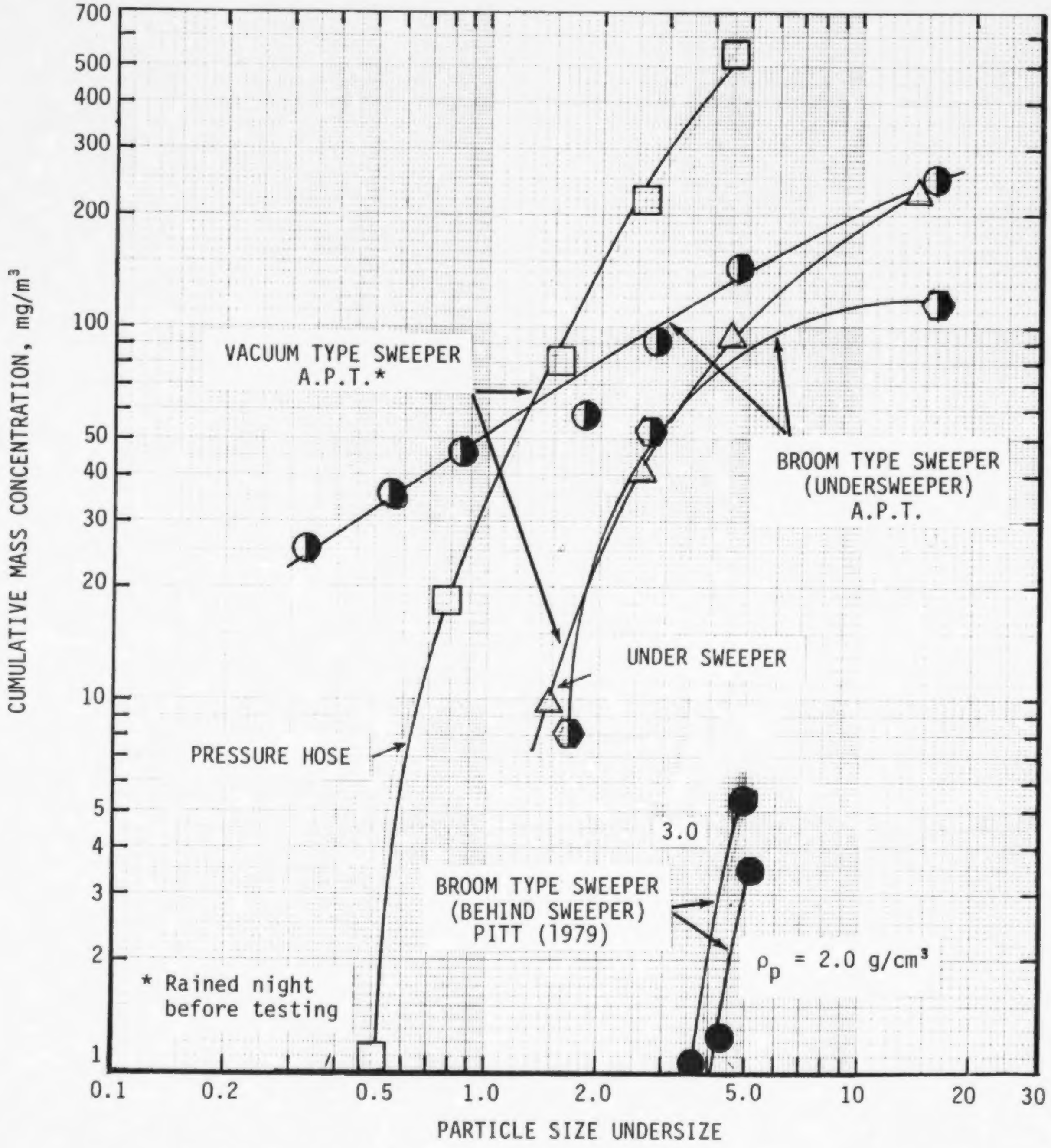


Figure 17. Comparison of cumulative mass concentration of dust dispersed by street sweepers. (Dry sweeping).

1. Water: The mean particle size of dust in these tests is considerably higher than previously reported data. The rain on the previous night agglomerated the dust and may have washed some of the fine dust away.

2. Street type: The size distribution of dust on streets varies with the street location. The tests were conducted on different streets which had different types of dirt.

3. Type of sweeper: Broom type and vacuum type sweepers were used to collect data presented in Figure 16 and 17. The sweepers have different dust pickup mechanisms which may alter the particle size distribution.

Section 5

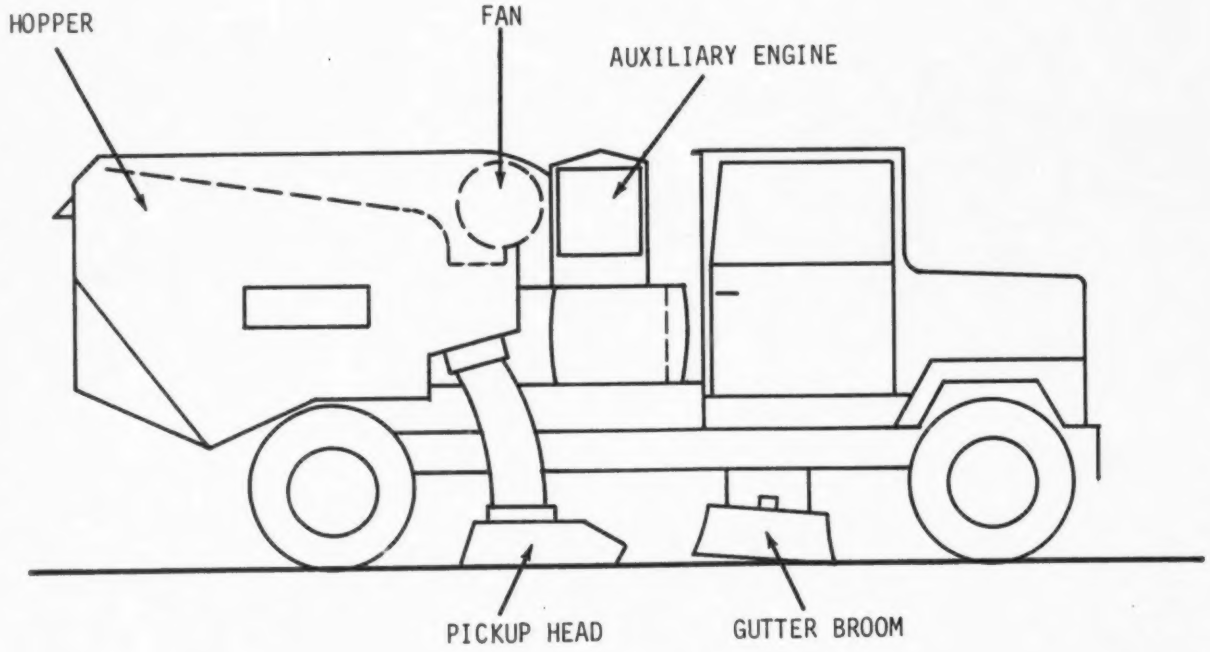
SWEEPER MODIFICATIONS

TYMCO MODEL 600 STREET SWEEPER

A Tymco Model 600 vacuum (regenerative air) street sweeper (Figure 18) was purchased for upgrading under this contract. Figure 19 shows a schematic diagram of the dust pickup mechanism of the sweeper. The gutter broom moves the street debris from the curb toward the center and the blast/vacuum pickup head which extends almost the entire width of the sweeper. The blower compresses air and forces it downward through the pressure hose and into and across the pickup head, creating a full width high velocity blast that lifts dirt and debris from the street toward the inlet. The blower creates a vacuum in the hopper that causes debris to be sucked up through the vacuum inlet and hose into the hopper, where the air loses velocity and heavy or large debris fall to the hopper floor. The air is drawn through a screen to remove paper and leaves, and then enters a centrifugal separator where large dust particles are removed and thrown into the hopper. The air is then sucked into the blower to start another cycle.

A positive pressure is maintained at the pickup head blast orifice, and a negative pressure in the pickup head vacuum inlet and in the hopper. The air flow rate and the static presure in the system can be varied by changing the blower speed. High blower speeds are used to pick up heavy materials and low blower speeds are used to pickup finer materials. Further, the vacuum in the pickup head can be increased by bleeding air out of the pressure hose. It is called the leaf bleeder system as it is used when picking up leaves.

Several nozzles are used in the hopper to wash the hopper during dumping, and one nozzle is directed at the gutter broom to suppress the dust clouds. The Tymco sweeper comes equipped with a 0.12 m^3 (30 gal) water tank and a pump with capacity rated at


HOPPER
FAN
AUXILIARY ENGINE
PICKUP HEAD
GUTTER BROOM

SCALE 1 cm≃0.5 m

Figure 18. Side View of TYMCO Vacuum (Regenerative Air) Sweeper

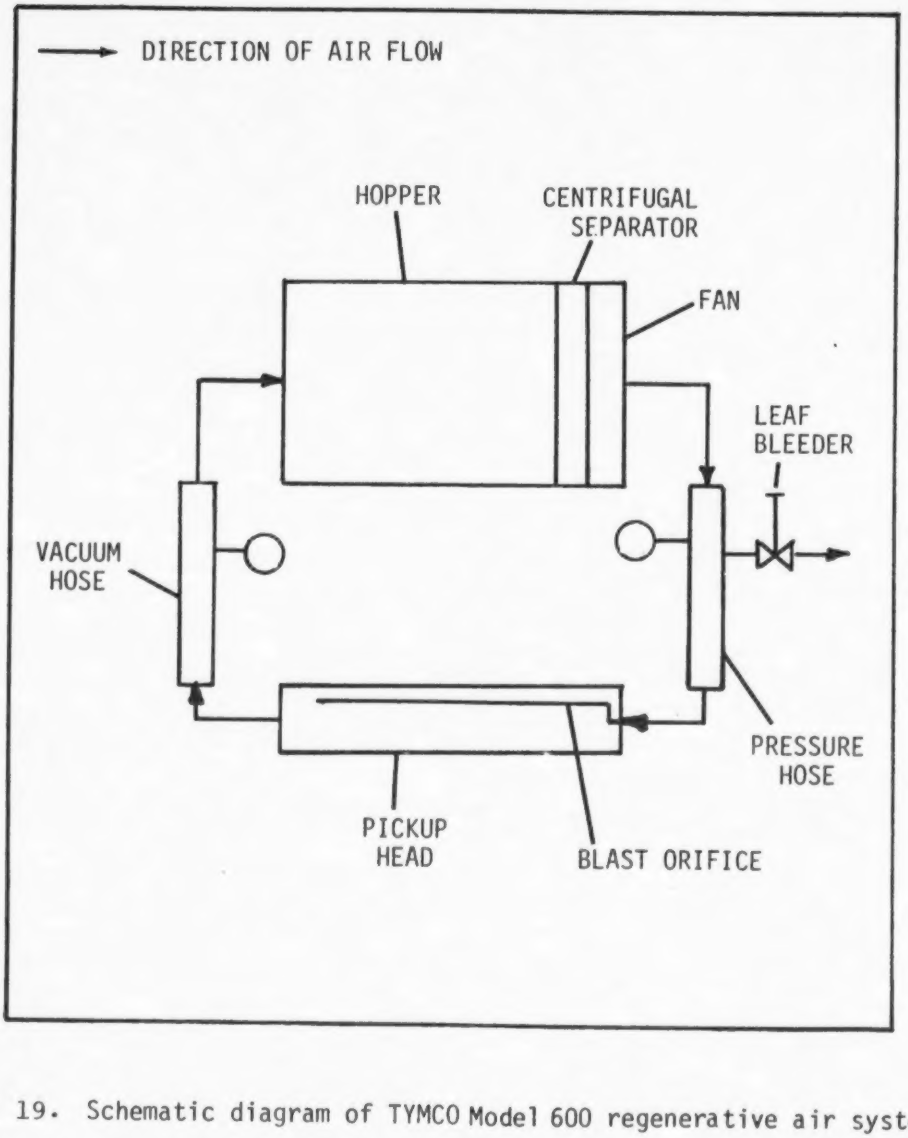

DIRECTION OF AIR FLOW
HOPPER
CENTRIFUGAL SEPARATOR
FAN
LEAF BLEEDER
VACUUM HOSE
PRESSURE HOSE
PICKUP HEAD
BLAST ORIFICE

Figure 19. Schematic diagram of TYMCO Model 600 regenerative air system

11.4 l/min at 4.2 MPa (3 gpm at 600 psi).

CONCEPTUAL DESIGN

Figure 20 shows the process design concept for improving the street sweeper performance. Containment and conveying of the dispersed dust is already accomplished to a large extent by the regenerative vacuum system of the Tymco sweeper. However, dust clouds were observed to occur at the gutter broom and the pickup head areas, and neither were controlled.

Controlling the dust clouds in the gutter broom area with sprays is not effective. A better method would be to enclose the gutter broom and vent the enclosure to the hopper. Since the hopper is under vacuum, in-bleed air will convey the contained dust to the hopper.

Dust clouds in the pickup head area were observed to occur when the pickup head travels on uneven street surfaces, such as pot holes and pebbles on the street. Pickup head dust clouds are eliminated by increasing the vacuum in the vacuum hose which causes an increase in the inward flow to the pickup head.

The vacuum in the vacuum hose could be increased by venting a small fraction of the recirculating air stream from the pressure hose. Venting from the pressure hose reduces the static pressure in the pressure hose, which in turn raises the vacuum in the hopper and the vacuum hose (because the developed pressure of the blower remains constant).

The vent air contains large quantities of inhalable particles, so it needs to be cleaned before discharging to the atmosphere. In the conceptual design, a charged spray scrubber is used because it can handle both dry and wet particles, such as mud.

PRELIMINARY EXPERIMENTS

Preliminary experiments were done to generate design information such as the amount of air to be vented and the drop size

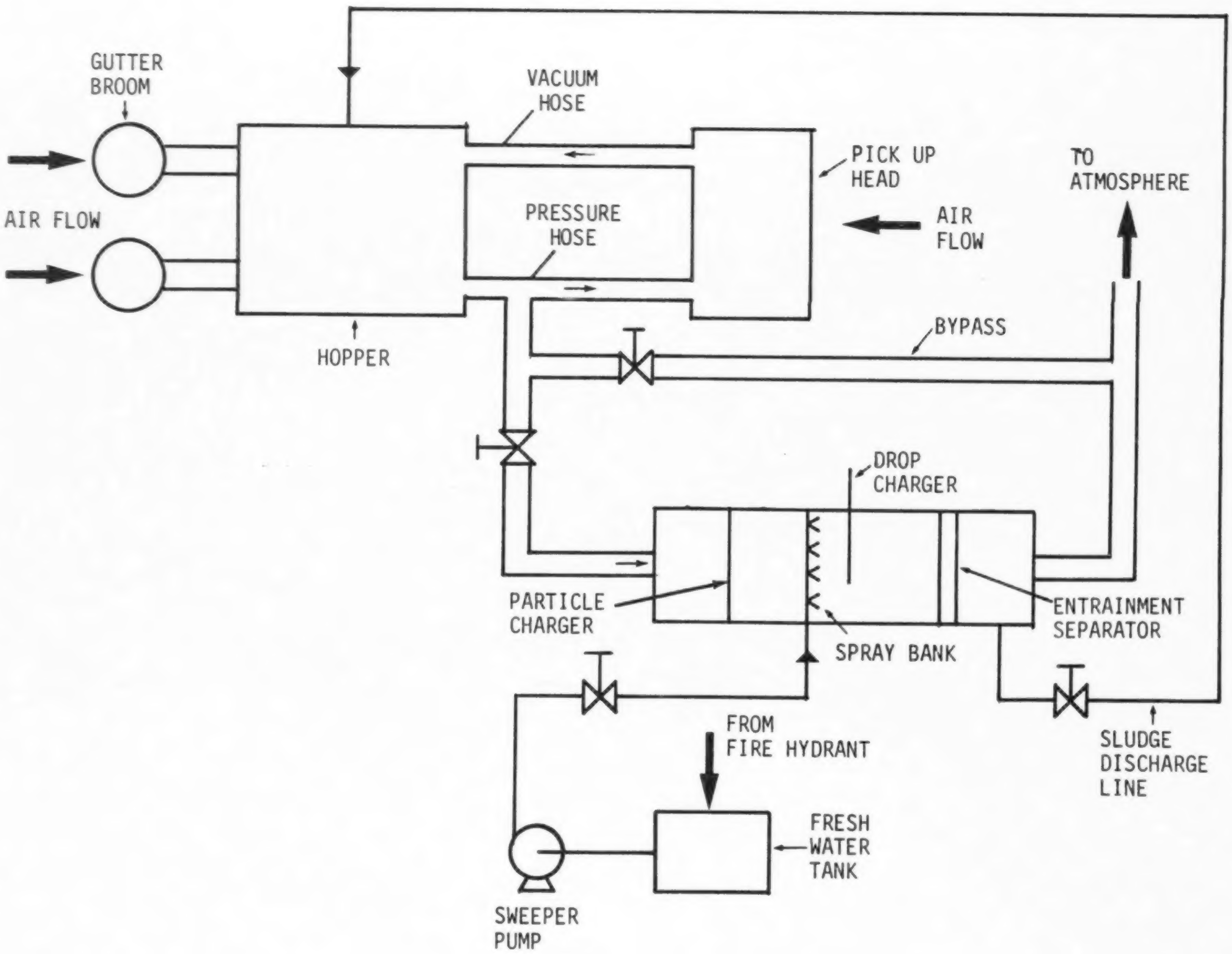

GUTTER BROOM
VACUUM HOSE
PICK UP HEAD
TO ATMOSPHERE
AIR FLOW
PRESSURE HOSE
AIR FLOW
BYPASS
HOPPER
DROP CHARGER
PARTICLE CHARGER
SPRAY BANK
ENTRAINMENT SEPARATOR
FROM FIRE HYDRANT
SLUDGE DISCHARGE LINE
FRESH WATER TANK
SWEEPER PUMP

Figure 20. Process diagram of improved street sweeper.

and liquid/gas ratio for the spray scrubber.

Air Flow Characteristics of the Sweeper

The sweeper air flow characteristics had to be measured in order to determine the air flow rate to be cleaned by the scrubber, and the air flow available to convey dust.

Air flow rates circulating in the sweeper were measured in the pressure and vacuum hoses. The pickup head was in the sweeping mode during the measurements. Data were collected with the auxiliary engine speed between 1,500 and 2,000 rpm. A standard pitot tube was used to measure the velocity pressure.

The air flow rates and static pressures in the pressure hose, vacuum hose and the hopper are reported in Table 10. Data indicate that the air flow rate circulating in the sweeper increases with the engine speed. Also, the vacuum in the hopper is increased when air is bled from the pressure hose. When the leaf bleeder valve was full open the vent air flow at 1500 rpm was about 33 Am^3/min (1,200 acfm), and the vacuum in the hopper increased by 7 cm W.C. at an engine speed of 2,000 rpm and by 3 cm W.C. at 1,500 rpm.

The required vent air flow rate was estimated from industrial ventilation practice to be 28 to 56 m^3/min (1,000 to 2,000 cfm). Therefore, it seems that the existing blower will suffice.

Spray Scrubber

The dust dispersed by the sweeper is contained and conveyed to a spray scrubber. For designing the spray scrubber, the dust was assumed to have a size distribution similar to that measured under the broom sweeper, i.e. $d_{pg} = 4$ μmA and $\sigma_g = 2.0$.

The spray scrubber needed to clean the vent air stream was established through a series of design studies. As the first step, the uncharged spray model by Calvert et al. (1975) was used:

Table 10. Air Flow Characteristics of the TYMCO Sweeper

		Leaf Bleeder Valve			
		Closed Engine Speed (rpm)		Open Engine Speed (rpm)	
No.	Item	2,000	1,500	2,000	1,500
1	Static pressure in pressure hose (cm W.C.)	26.7	16.0	13.3	6.1
2	Static pressure in vacuum hose (cm W.C.)	-16.0	-8.9	-25.1	-14.7
3	Vacuum in hopper (cm W.C.)	-16.0	-8.4	-23.2	-11.2
4	Flow rate in pressure hose				
	(Am^3/min)	141.6	106.6	--	--
	(Nm^3/min)	145.2	108.2	--	--
5	Flow rate in vacuum hose				
	(Am^3/min)	133.4	97.9	169.5	138.4
	(Nm^3/min)	131.4	97.0	165.4	136.4
6	Flow rate vented at the leaf bleeder				
	(Am^3/min)	--	--	34.8	33.1
	(Nm^3/min)	--	--	28.2	26.9

$$Pt_d = \exp \quad - \frac{1.5Q_L}{Q_G\ d_d} \int_o^{R_d} \eta\ f_A\ dx \qquad (3)$$

where: Pt_d = particle penetration for diameter "d_{pa}", fraction

d_d = drop diameter, cm

Q_G = gas flow rate, cm³/s

Q_L = liquid flow rate, cm³/s

R_d = drop range or distance traveled by drop relative to the gas, cm

f_A = fraction of gas flow cross-section covered by sprays, fraction

η = instantaneous single drop collection efficiency

x = coordinate in gas flow direction, cm

A representative set of predictions based on this model is shown in Figures 21 and 22, plots of particle penetration versus liquid/gas ratio, with particle aerodynamic diameter as the parameter.

Both plots are based on experimentally determined single sphere collection efficiency (Walton and Woolcock, 1960), 300 μm diameter water drops, and 50 cm drop range. The drop range is the distance traveled by a drop relative to the air and is limited by the drop trajectory or by the dimensions of the scrubber. Figure 21 is for an initial drop velocity of 30 m/s relative to the air and Figure 22 is for 20 m/s.

Overall particle penetration, Pt, was predicted for an uncharged spray scrubber with the assumed inlet particle size distribution. A water flow rate of about 1.6 l/m³ (12 gal/Mcf) would be required to attain Pt, = 0.1 with 300 μm drop diameter and 30 m/s initial velocity. Since the water holding capacity of a street sweeper is limited, the water flow rate is too high to be practical. It is clear that the spray scrubber must be augmented. The approach taken in this study was to use electrostatic augmentation to enhance the collection of fine

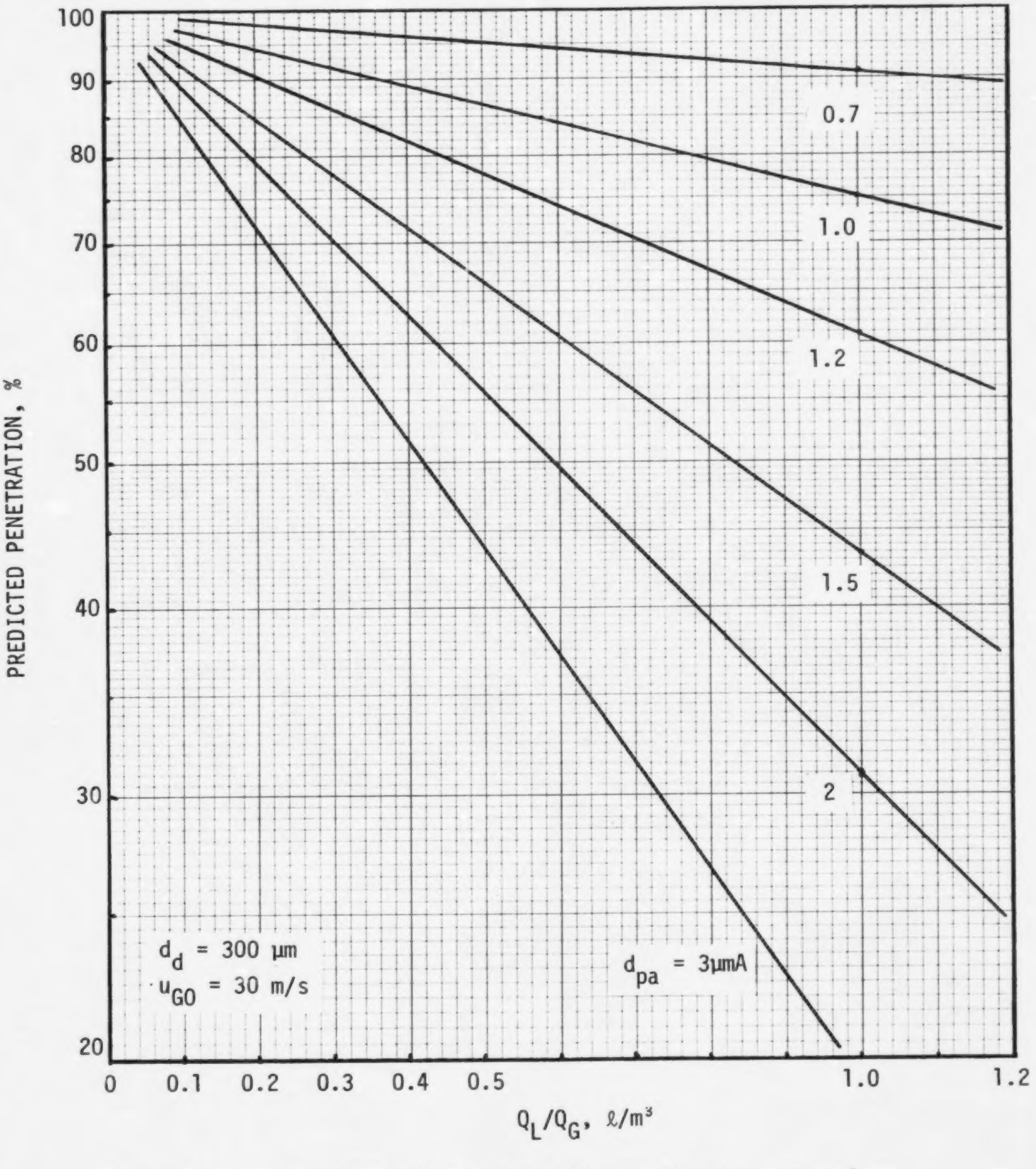


Figure 21. Predicted penetration for 300 μm diameter spray drop scrubbing.

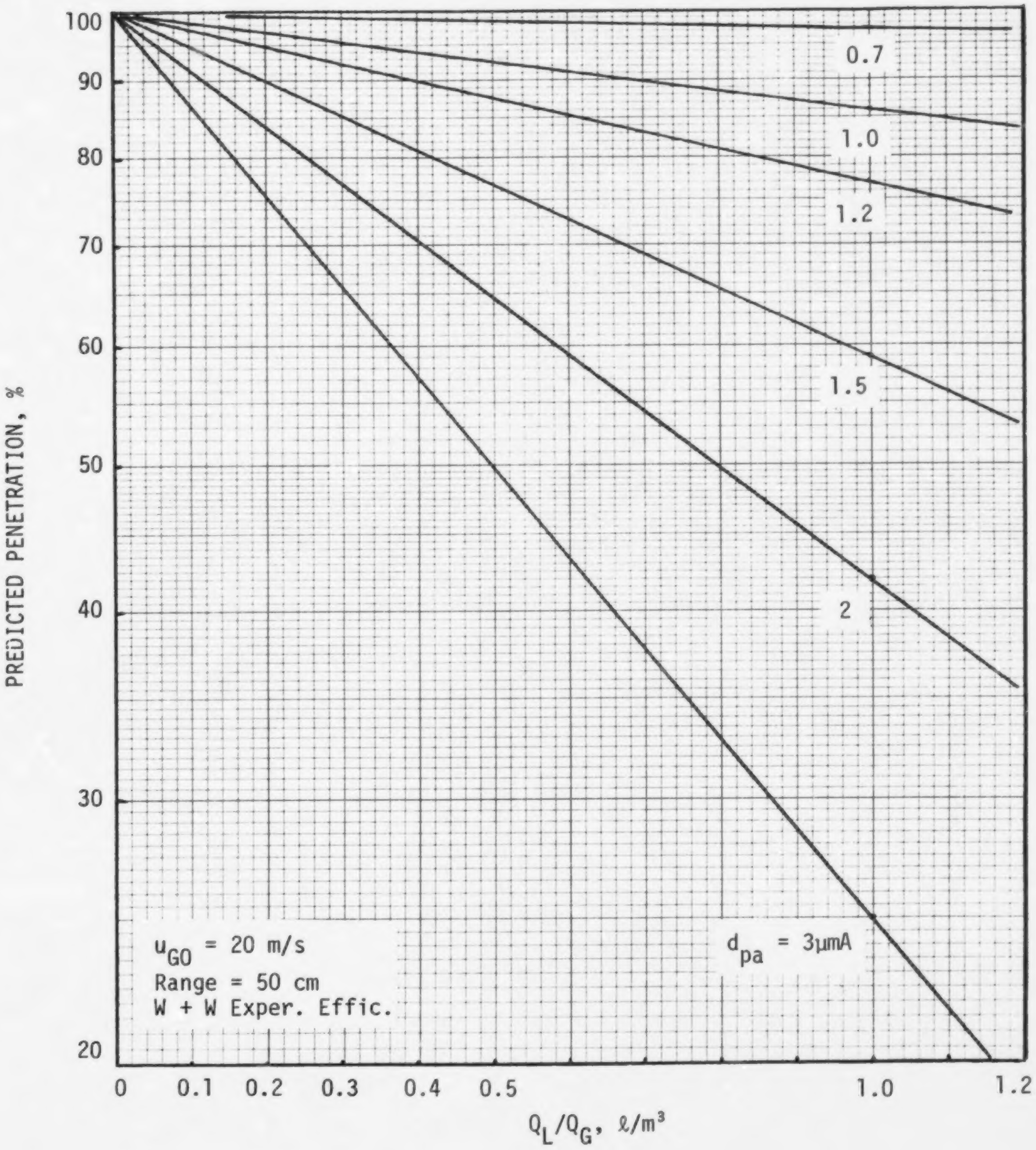


Figure 22. Predicted penetration for 300 µm diameter spray drop scrubbing.

particles (d_{pa} <3 μmA).

The effect of electrostatic augmentation of particle collection by sprays can be predicted if one can account for the combined influences of electrostatic and inertial deposition. Nielsen (1974) presented the results of his computations of predicted particle collection efficiency for single drops for the cases of:

1. Inertial impaction (NP/ND, Neutral Particle/Neutral Drop).
2. Coulombic attraction (CP/CD).
3. Charged particle image force (CP/ND).
4. Charged collector image force (NP/CD).

Nielsen's plots of collection efficiency against inertial impaction parameter and his electrostatic deposition parameters can be used to predict the efficiency of a spray drop at various points along its trajectory. It can be shown that coulombic attraction is the only mechanism which could cause a significant increase in the collection efficiency of an electrostatically augmented spray scrubber. Consequently, we have predicted the effect of Coulombic attraction on a spray scrubber and compared the predictions with our experimental results.

Nielsen's Coulombic attraction parameter, K_c, is defined as:

$$K_c = - \frac{Q_c \quad Q_p \quad C'}{3\pi^2 \, k_f \, d_c^2 \, d_p \, \mu_G \, u_r} \qquad (4)$$

where K_c = coulombic attraction parameter, dimensionless

Q_c = charge on collector, Coulombs

Q_p = charge on particle, Coulombs

C' = Cunningham slip factor, dimensionless

k_f = dielectric constant of gas, 8.854×10^{-12} F/m

d_c = collector diameter, m

d_p = particle dimeter, m

μ_G = gas viscosity, kg/m-s

u_r = gas velocity relative to collector, m/s

The relationship between particle collection efficiency, "K_c", and "K_p", as computed by Nielsen is illustrated in Figure 23. Note that the values of "K_c" are negative, signifying that the particles and drops are oppositely charged. It can be seen that the greatest effect of Coulombic attraction occur when "K_p" is small, which corresponds to small values of relative velocity, "u_r." Since "K_c" is inversely proportional to "u_r", it increases as "K_p" decreases, thus intensifying the predicted influence of Coulombic attraction.

Average Drop Efficiency

The efficiency shown in Figure 23 is an instantaneous value, while the spray scrubbing model requires accounting for particle collection over the total path the drop travels. Drop trajectories were taken from the computations of Walton and Woolcock (1960) and are shown in Figure 24, a plot of drop velocity vs. drop "range" (i.e., the distance traveled by the drop) for drops of several diameters and with an initial velocity of 30 m/s. A 100 µm diameter drop sprayed into air at a velocity of 30 m/s would travel 30 cm relative to the air, while a 200 µm diameter drop would go about 90 cm.

Given the drop velocity at all positions along its range and the instantaneous efficiency correlation of Figure 23, collection efficiency for all points on the range can be computed. Figure 25 is a plot of predicted particle (d_{pa} = 0.6 µmA) collection efficiency vs. drop range for charged particles with charged drops (CP/CD) and for neutral particles and drops (NP/ND). The two sets of curves shown are for 100 µm and 250 µm diameter drops.

The charge level on the drops was computed from experimental data of Yung et al. (1981), which indicated a charge of approximately 5×10^{-7} C/g for drops of 200 µm to 500 µm diameter, with induction charging. For 250 µm dia. drops this is about 15% of the Rayleigh limit, while for 100 µm dia. drops it is only 3.7% of the limit. The particle charge levels were computed for a

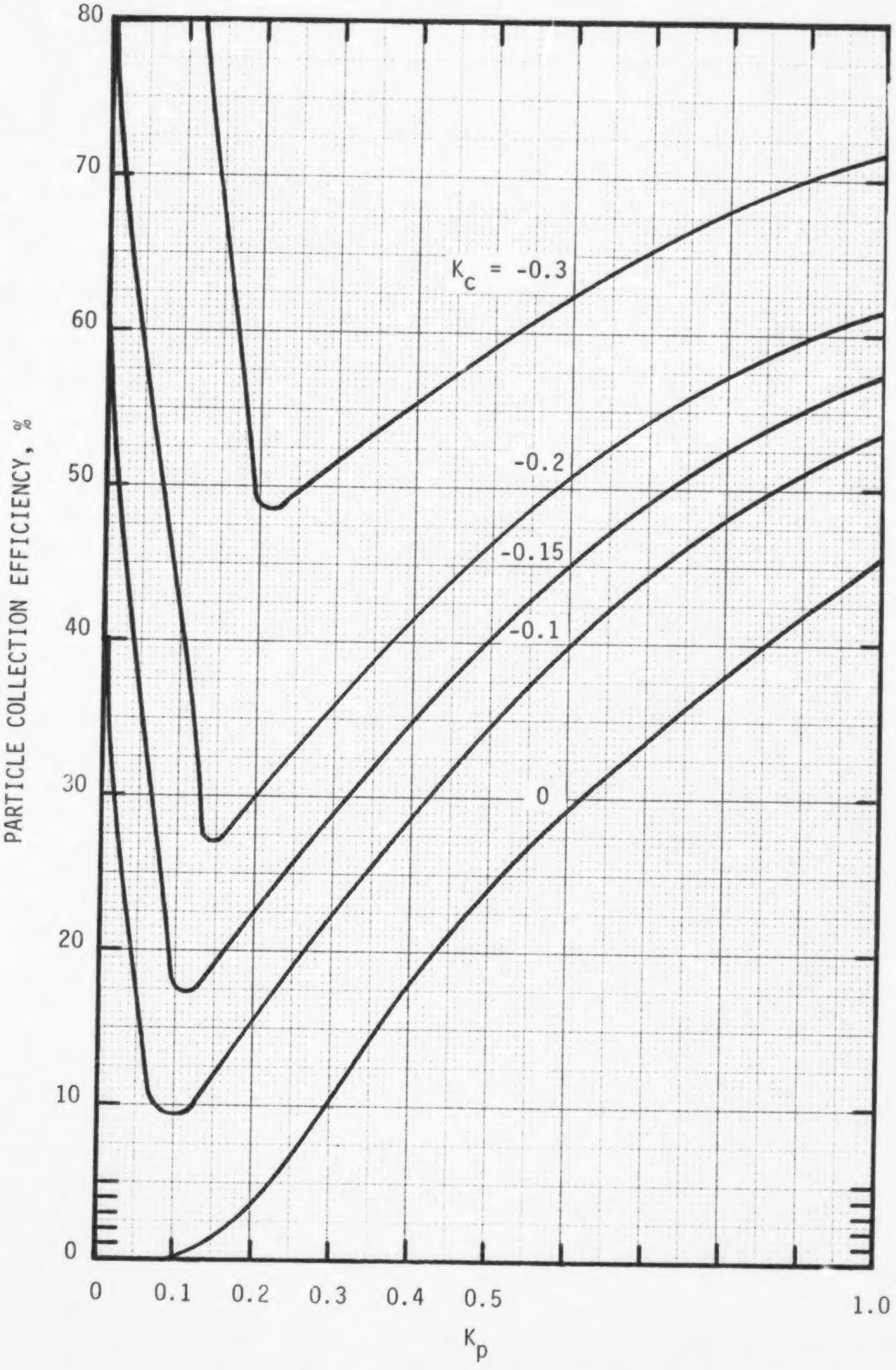


Figure 23. Predicted efficiency for coulombic attraction and inertial impaction.

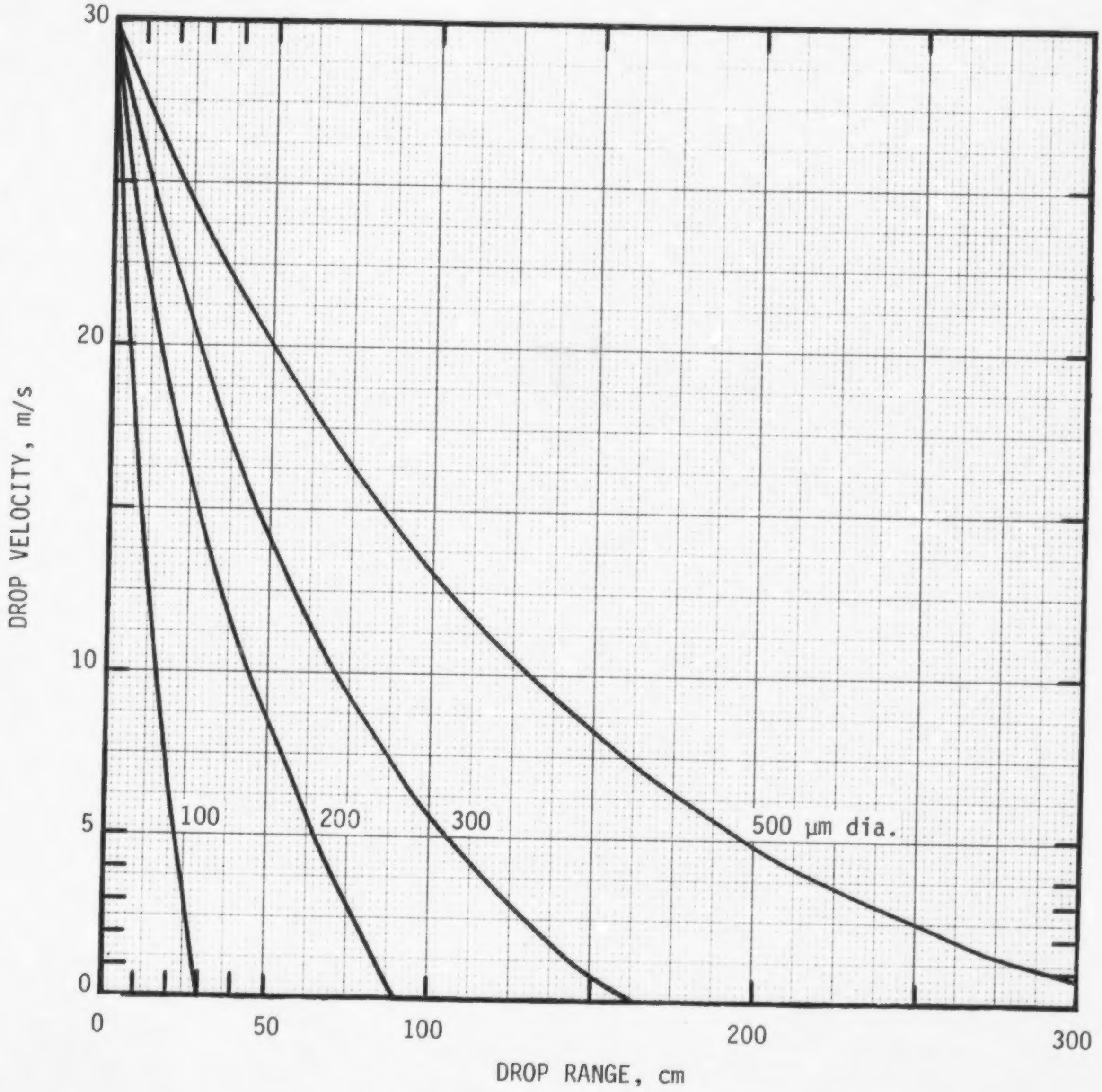


Figure 24. Trajectories for water drops in air.

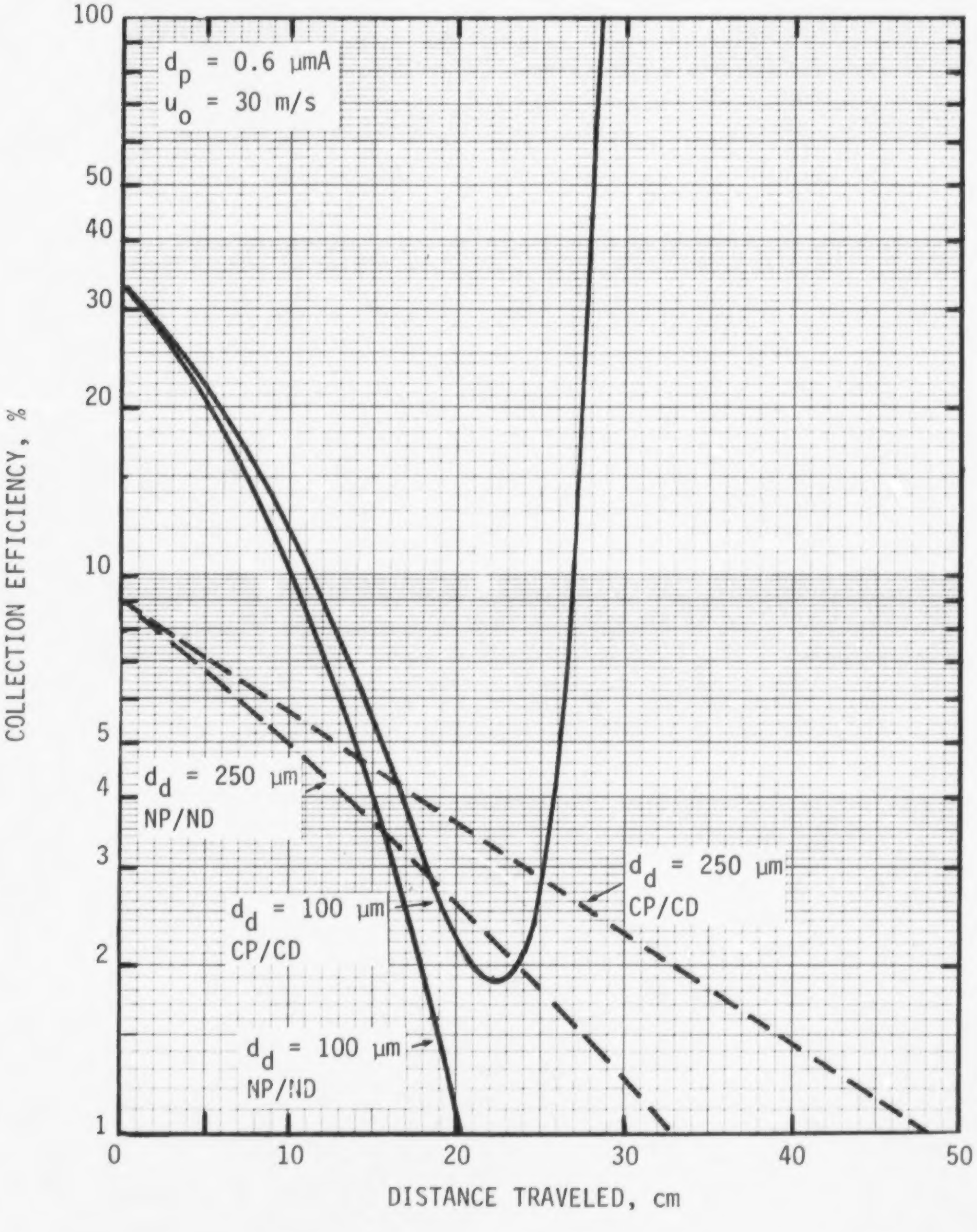


Figure 25. Collection efficiencies of neutral and charged drops for 0.6 μmA diameter particles.

corona charger with a field strength of 4 x 10^5 V/m.

Figure 25 shows that the greatest effect of charging occurs after the drops have slowed to the point where inertial impaction becomes unimportant. Since the average efficiency is obtained by integrating over the drop range, it is strongly influenced by how much of the drop range is considered. In the scrubber configuration envisioned for the street sweeper, the drop range, R_d, is about 50 cm. This is the distance the drop would go from the point of atomization to the scrubber wall.

A 50 cm range limit presents no problem for a 100 μm dia. drop, whose range would only be 30 cm if its initial velocity were 30 m/s. For a 250 μm dia. drop the 50 cm range limit eliminates the most effective part of the drop trajectory. This fact has obvious importance in the designing of a charged spray scrubber, as will be discussed later.

Average efficiencies for 100 μm and 250 μm dia. drops were computed by integration over drop trajectories and are given in Table 11. Also shown in Table 11 are the computed penetrations for a spray scrubber with a water/air ratio of 0.4 l/m^3. Penetrations were computed from:

$$Pt_d = \exp -\left[\frac{3\ R_d\ Q_L\ \bar{\eta}}{2\ d_d\ Q_G}\right] \qquad (5)$$

where Pt_d = penetration for a given particle size, fraction
Q_d = liquid flow rate, m^3/s
Q_G = gas flow rate, m^3/s
$\bar{\eta}$ = average collection efficiency over drop range, fraction

Note that the range, R_d used is the smaller of the drop range and the range limit. Thus, R_d = 30 cm for d_d = 100 μm and 50 cm (limit) for d_d = 250 μm.

The influence of drop diameter is clearly shown. Despite their smaller range, 100 μm dia. drops would be much more effective than 250 μm dia. drops.

TABLE 11. AVERAGE COLLECTION EFFICIENCIES OF DROPS AND SPRAY PENETRATIONS

d_{pa}, µmA	d_d, µm	R_d, cm	u_o, m/s	$\bar{\eta}$, % NP/ND	$\bar{\eta}$, % CP/CD	Pt @ 0.4 NP/ND	l/m^3, % CP/CD
1.0	250	50	20	12.4	15.0	86	84
0.6	250	50	20	1.4	1.8	98	97.8
1.0	250	50	30	22.2	24.0	77	75
0.6	250	50	30	2.8	3.4	97	96
1.0	100	30	30	28.0	33.0	60	55
0.6	100	30	30	8.6	11.5	86	81

We may also note that higher charge on the drops would have a large effect. For instance, if the charge level on 100 μm dia. drops were 10% of the Rayleigh limit, the average efficiencies for 0.6 μmA and 1.0 μmA particles would be 30% and 47%, respectively. Comparison with the values given in Table 11 for a lower drop charge level shows the extent of improvement better charging would cause.

Experiments

Experiments were done on the charged spray scrubber built under the EPA Contract No. 68-02-3109 (Yung et al., 1981) to determine the particle capture efficiency. A schematic diagram of the equipment is shown in Figure 26. Hydrated lime aerosol is fed into the blower and the particles are charged by a wire and rod charging grid. Particles are then collected by charged water drops which are sprayed from pressure nozzles and induction charged by means of a grid. The water drops are removed from the air flow by an entrainment separator and the "clean" air is vented to the atmosphere. The particle penetration through the charged spray scrubber is determined by sampling simultaneously at the inlet and outlet ports with cascade impactors.

Figures 27 through 31 show the experimental penetration curves. The superficial gas velocity and liquid-to-gas ratio were 2.9 m/s and 0.4 l/m^3 (3 gal/Mcf) for all experiments. The first two runs (72/09/03 and 72/09/04) used pigtail nozzles and the other runs used pin type nozzles. Nozzle pressure was about 450 kPa (50 psig). The drop diameter was measured to be 300 μm and 240 μm for the pigtail and hook type nozzles, respectively. The charges on particles and drops were -1.1×10^{-6} C/g and 5.8×10^{-7} C/g, respectively (see Yung et al., 1981, for drop diameter and charge measurement methods).

As can be seen from Figures 27 through 29, charging the water drops or the particle augmented the collection of fine particles. Further improvement in efficiency was obtained when

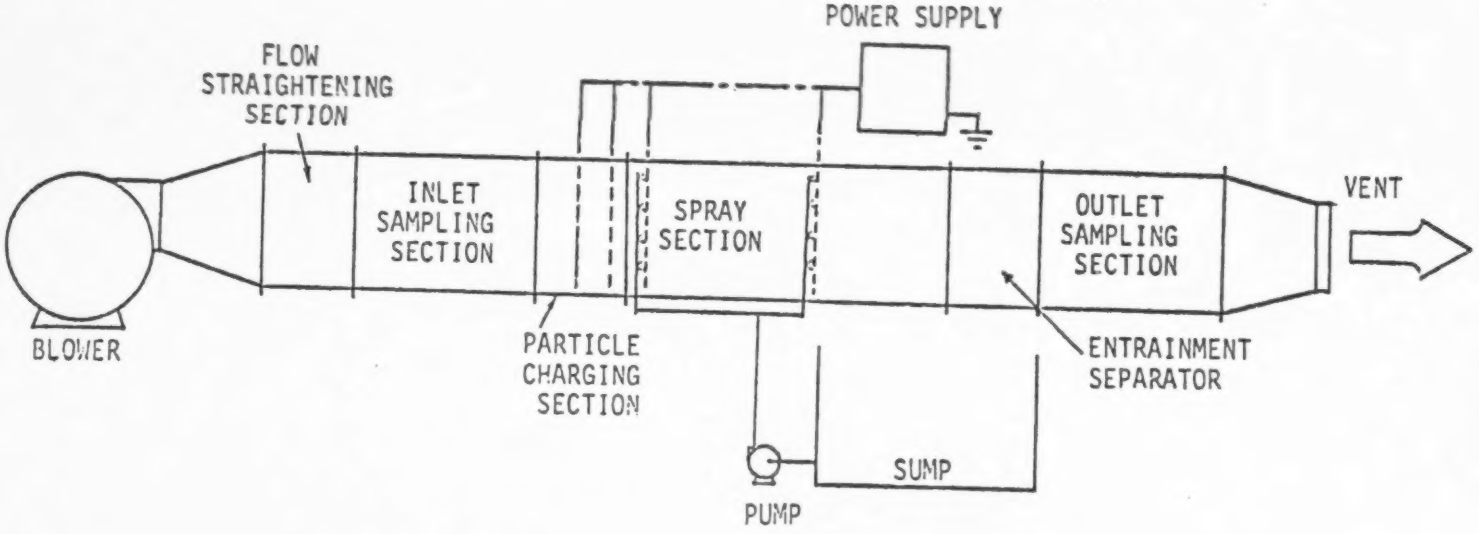

POWER SUPPLY
FLOW STRAIGHTENING SECTION
INLET SAMPLING SECTION
SPRAY SECTION
OUTLET SAMPLING SECTION
VENT
BLOWER
PARTICLE CHARGING SECTION
ENTRAINMENT SEPARATOR
PUMP
SUMP

Figure 26. Experimental apparatus for measuring particle collection efficiency of a charged spray scrubber.

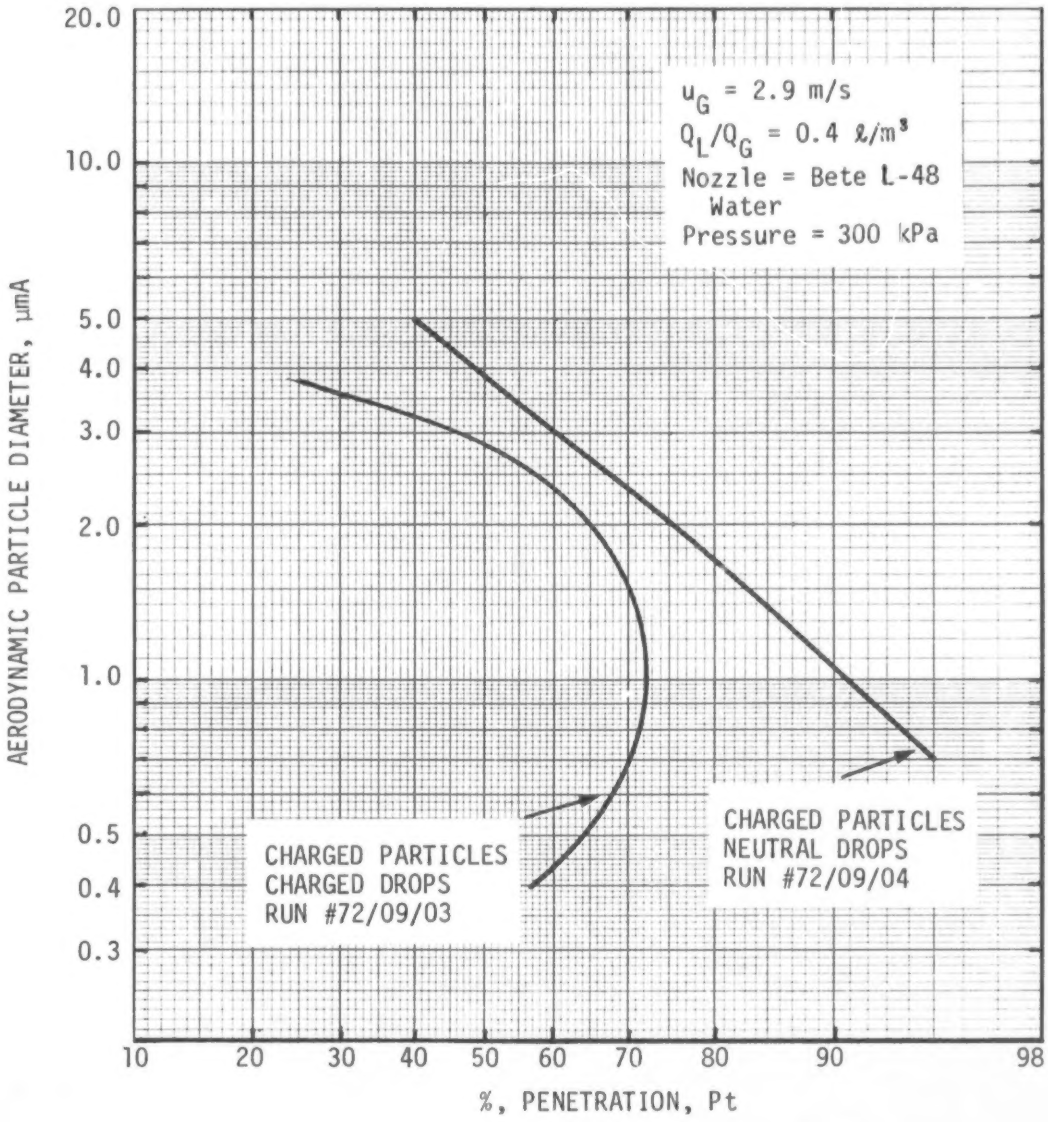


Figure 27. Measured spray scrubber particle penetration, Test 1.

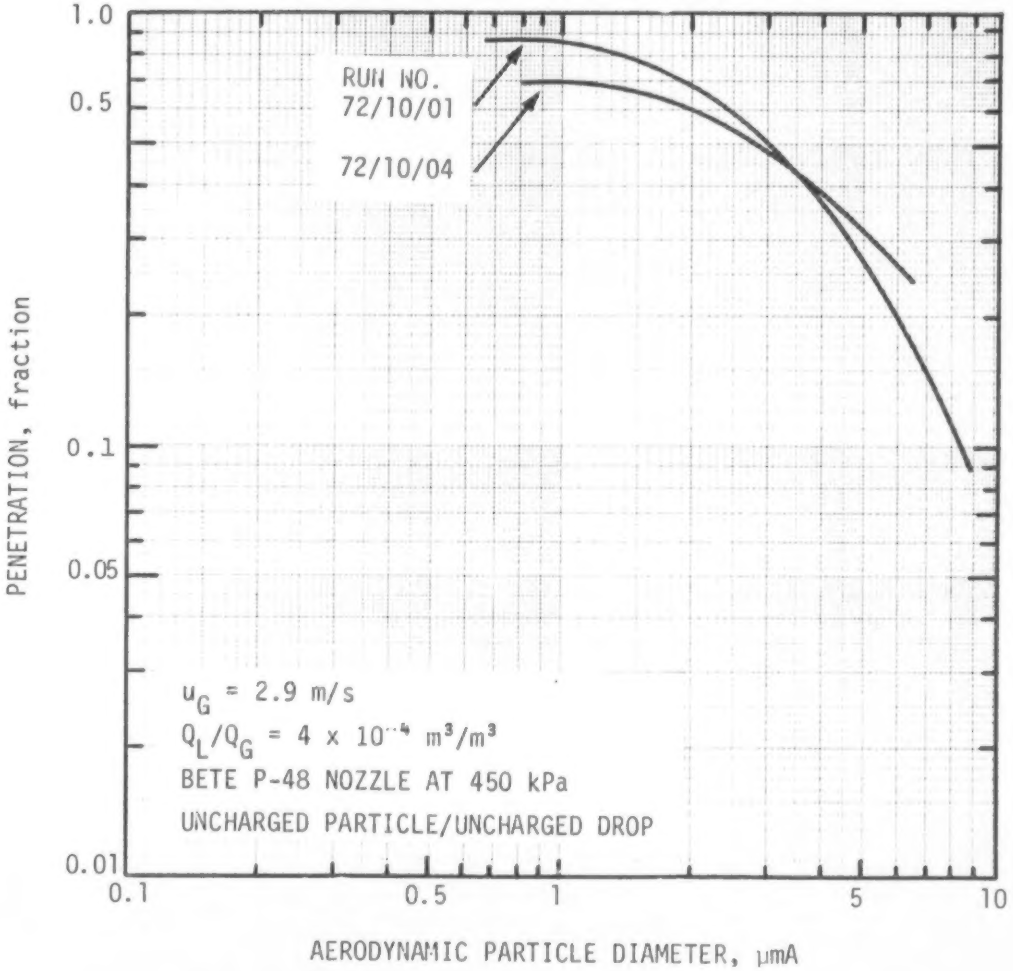


Figure 28. Measured spray scrubber penetration.

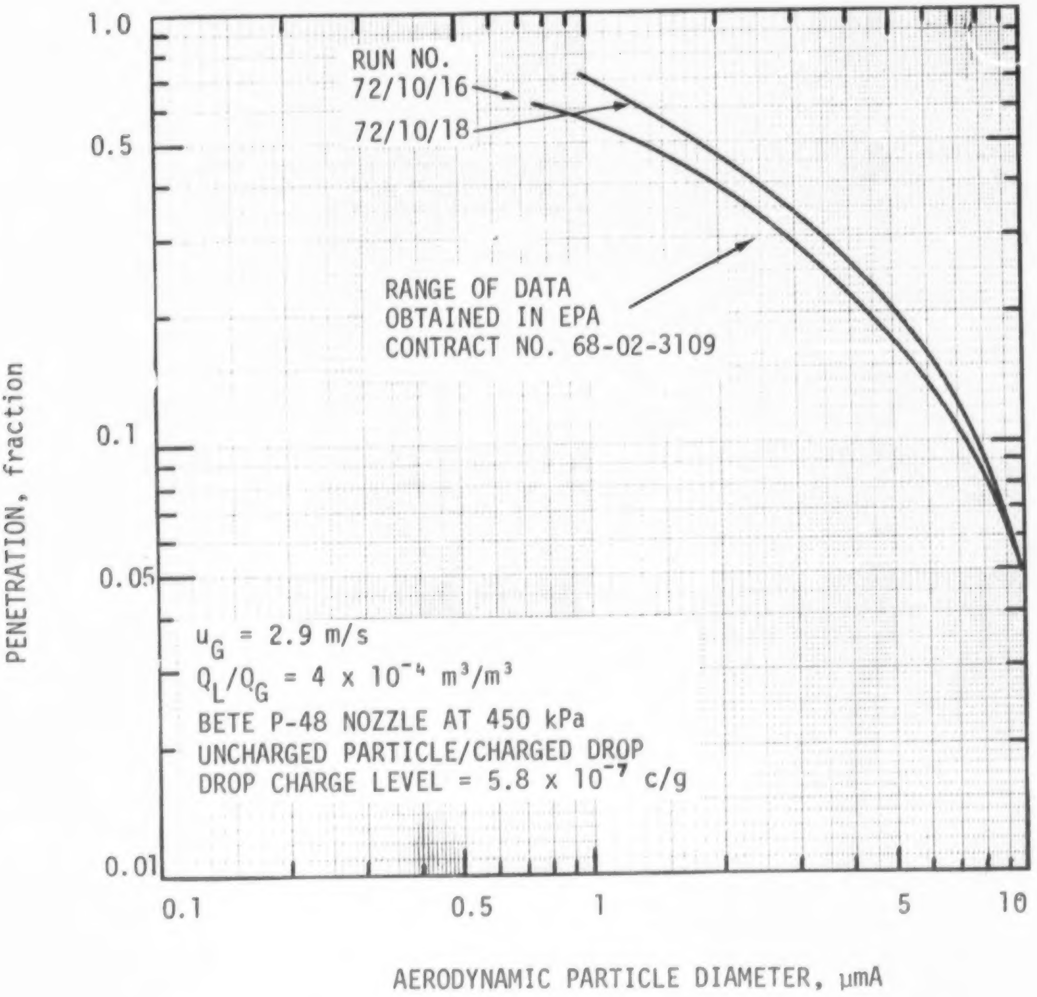


Figure 29. Measured spray scrubber penetration

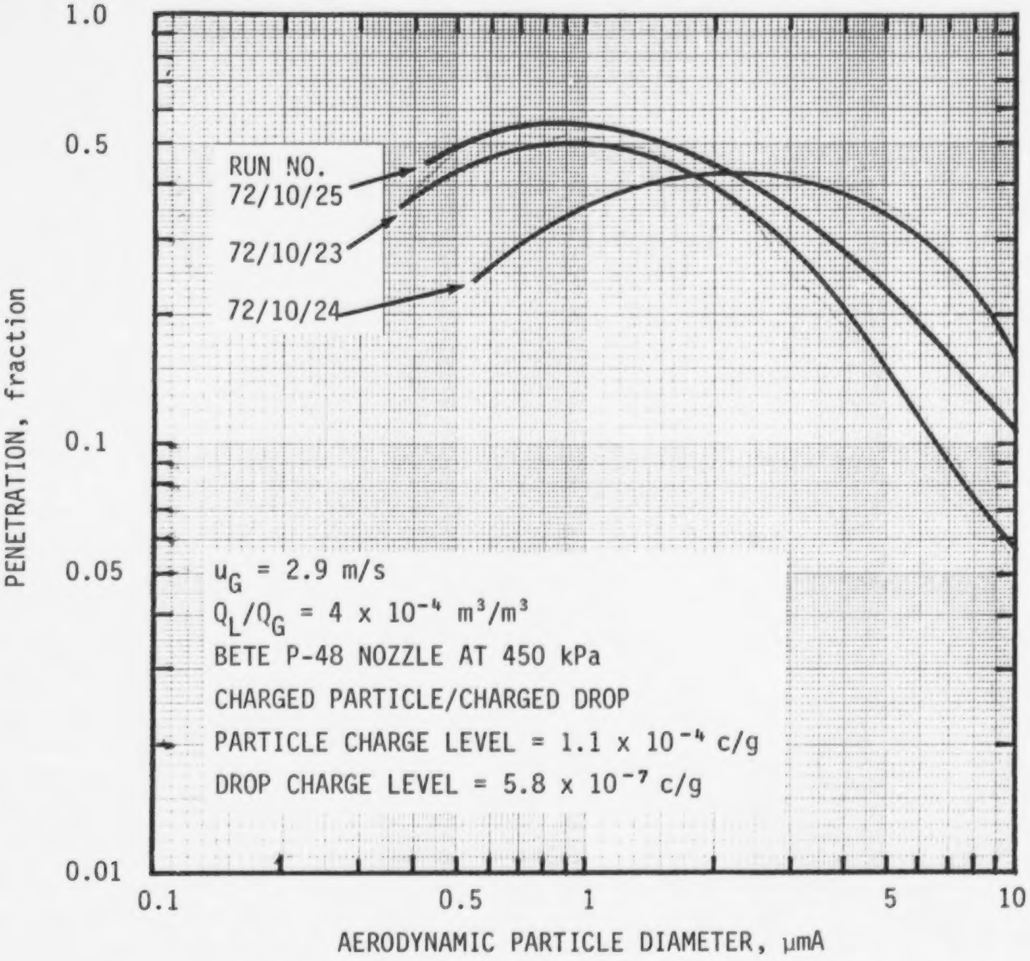


Figure 30. Measured spray scrubber penetration

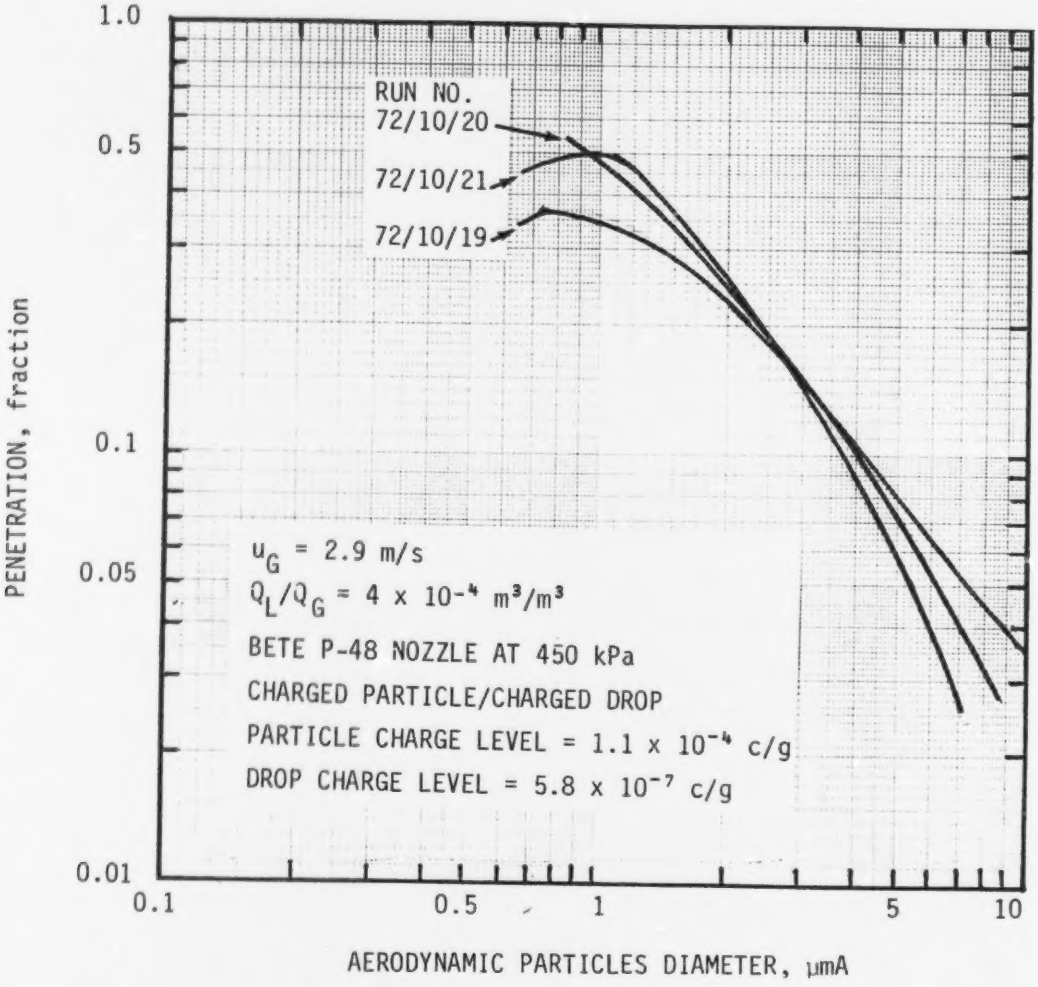


Figure 31. Measured particle charger and spray scrubber penetration

opposite charges were placed on the drops and the particles.

Discussion

While the model predicts no significant effect of charging for 250 μm dia. drops, experimental results show a large increase in efficiency for the smaller particles. The discrepancy may be due in part to the large effects of drop range and drop diameter. If the drops travel farther than 50 cm before striking a wall and if the effective average drop diameter is smaller than 250 μm, the predicted efficiency would be higher.

The overall penetration, which was computed with the experimental grade penetration and the assumed inlet particle size distribution, was 12.5% for a liquid/gas ratio of 0.4 l/m^3 and $d_d = 240$ μm. The calculated overall penetration was slightly higher than the target of 90% efficiency. To obtain 90% efficiency, smaller spray drops (which have higher efficiency) or a higher liquid/gas ratio must be used. Using smaller spray drops is a better approach because of limited holding capacity of the water tank on the street sweeper.

Bench scale experiments on the charged spray scrubber indicated that particle collection efficiency could be increased by using fine water drops. A survey of single fluid spray nozzles available in the market was conducted. It was found that the opposed jet type and pin type nozzles can give fine atomized sprays. The flow characteristics of these nozzles with the Tymco piston pump on the sweeper were measured and are presented in Table 12. The opposed jet nozzle has a higher liquid flowrate and it generates smaller drop than the pin jet type nozzle.

Drops could be charged by induction by either connecting the high voltage terminal directly to the nozzle or to a grid in the proximity of the nozzle. Connecting the high voltage terminal directly to the nozzle would not be practical for the sweeper because it is necessary to isolate the pump, the water tank, and pipes. Charging by the second method is simpler. In order for the drops to be charged properly, the high voltage grid should be

TABLE 12. DATA ON FINE SPRAY NOZZLES

Aux. Engine Speed	PIN TYPE NOZZLE P-48			OPPOSED JET NOZZLE #22477611		
	Pressure kPa	Water Flow Rate m^3/s	Mass** Medium Drop Diameter µm	Pressure kPa	Water Flow Rate m^3/s	Mass** Medium Drop Diameter µm
1,500	3,400*	3.8×10^{-5}	100	1,378	1.3×10^{-4}	55
2,000	3,400*	8.8×10^{-5}	100	2,067	1.7×10^{-4}	50

*Pressure relief valve was set at 3,400 kPa

**Data provided by manufacturer

placed at the location where the liquid sheet from the nozzle breaks into drops.

Because it can generate smaller drops, the opposed jet nozzle was initially chosen as the nozzle to be used in the spray scrubber. However, problems arose in trying to charge the water drops. The liquid sheet from the nozzle is small and too close to the nozzle. The high voltage grid cannot be placed close by.

The pin type spray nozzle was finally chosen. This nozzle can provide 100 μm diameter drops at high pressure (4.2 MPa, 600 psi).

DETAILED DESIGN

Figure 32 shows the modified sweeper layout. The dust clouds in the gutter broom area were controlled by enclosing the broom with a hood and venting to the hopper through 15 cm I.D. flexible hose and piping. A damper valve in the pipe section controls the air flow from the hood to the hopper.

Figure 33 shows the dimensions of the scrubber which was designed for a maximum flow rate of 56 m^3/min (2,000 cfm). A wire and rod type particle charger was built into the scrubber to pre-charge the particles. The particle charger consisted of two rows of corona wires. Wire diameter was 0.18 mm (0.007 in.). The spacing between wires within the same row was 11.4 cm (4.5 in.). The ground electrodes were 2.67 cm O.D. pipe. The cross-section of the charger was 45.7 cm x 45.7 cm, which was smaller than the scrubber shell cross-section so that all electrical connections could be hidden inside the shell.

Four equally spaced pin type nozzles were placed 15 cm downstream from the particle charger. The spray was co-current with gas flow and was charged by induction, with the nozzles maintained at ground potential and a high voltage ring in front of each nozzle. The overall length of the spray section was 91.5 cm (3 ft).

A 15 cm (6 in.) thick knitted mesh entrainment separator was used to remove water drops as well as large solid particles. The

SCALE APPROXIMATELY 1 cm = 0.6m

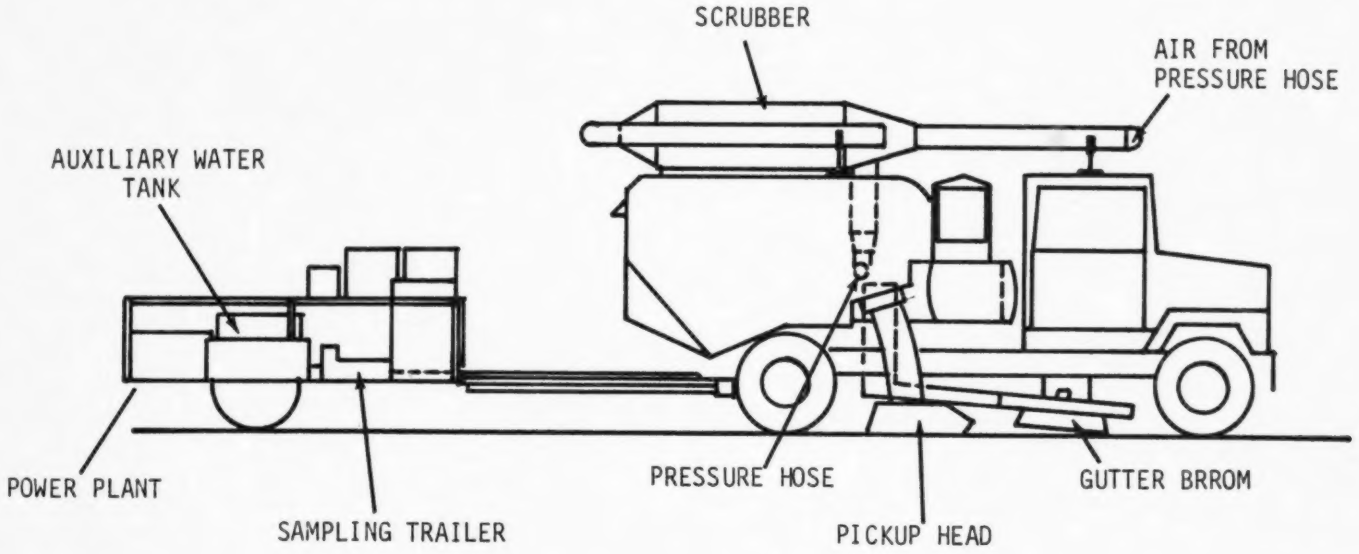

SCRUBBER
AIR FROM PRESSURE HOSE
AUXILIARY WATER TANK
POWER PLANT
SAMPLING TRAILER
PRESSURE HOSE
PICKUP HEAD
GUTTER BRROM

Figure 32. TYMCO street sweeper and trailer.

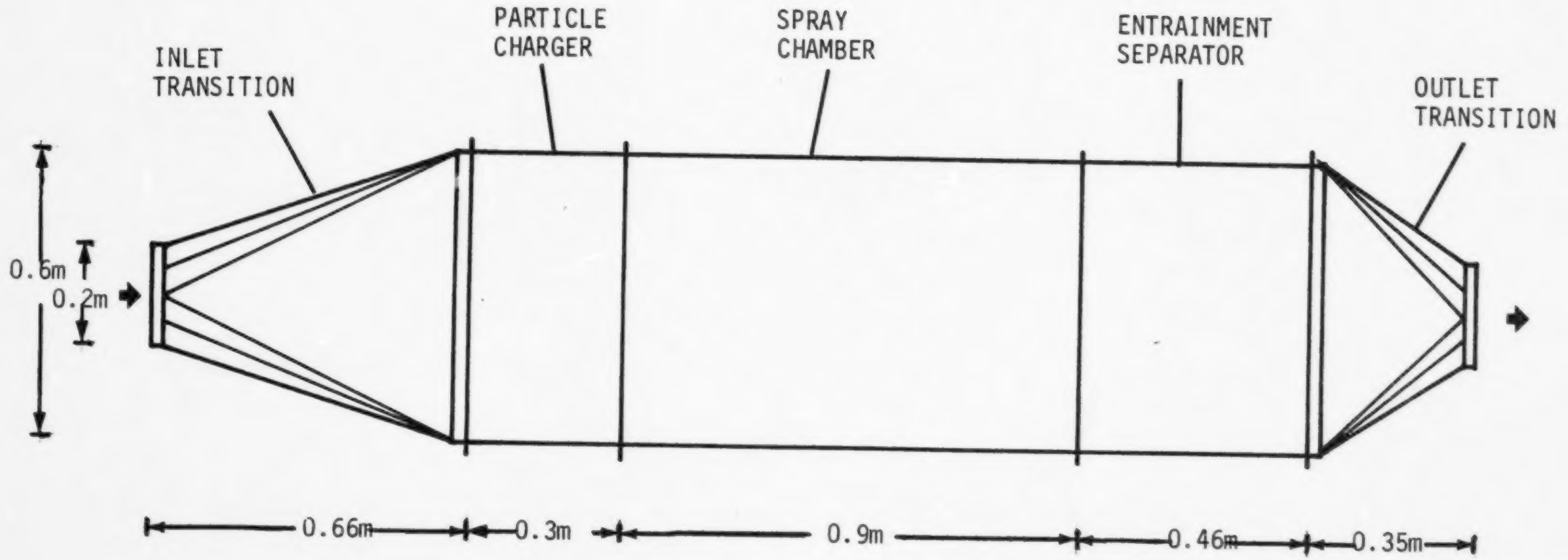

INLET
TRANSITION
PARTICLE
CHARGER
SPRAY
CHAMBER
ENTRAINMENT
SEPARATOR
OUTLET
TRANSITION
0.6m
0.2m
0.66m
0.3m
0.9m
0.46m
0.35m

Figure 33. Scrubber shell.

air velocity at the upstream face of the entrainment separator was increased by blocking about 50% of the flow area so that the cut diameter of the entrainment separator would be 3 μmA.

In an actual system, the scrubber could be located inside the hopper. For purposes of sampling and easy access, the scrubber was mounted on top of the sweeper and water was drained into the hopper.

Gas flow rate through the scrubber was measured with a Venturi meter, and was controlled by a damper. The sampling system provides for the measurement of air flow from the gutter-brooms to the hopper inlet. Particle size and concentration were measured with cascade impactors. Sample ports were provided for the scrubber inlet and outlet at locations at least 8 duct diameters from upstream transitions or bends. Sample trains of the type used for EPA Method 5 were used. Due to space limitations on the sweeper, the sample trains were placed on a trailer pulled by the street sweeper. Additional utilities, such as the power plant for supplying electricity to the sampling pump, the high voltage power supplies, auxilliary water tank, and the transfer pump, were also placed on the trailer. Figure 34 shows the sampling trailer layout.

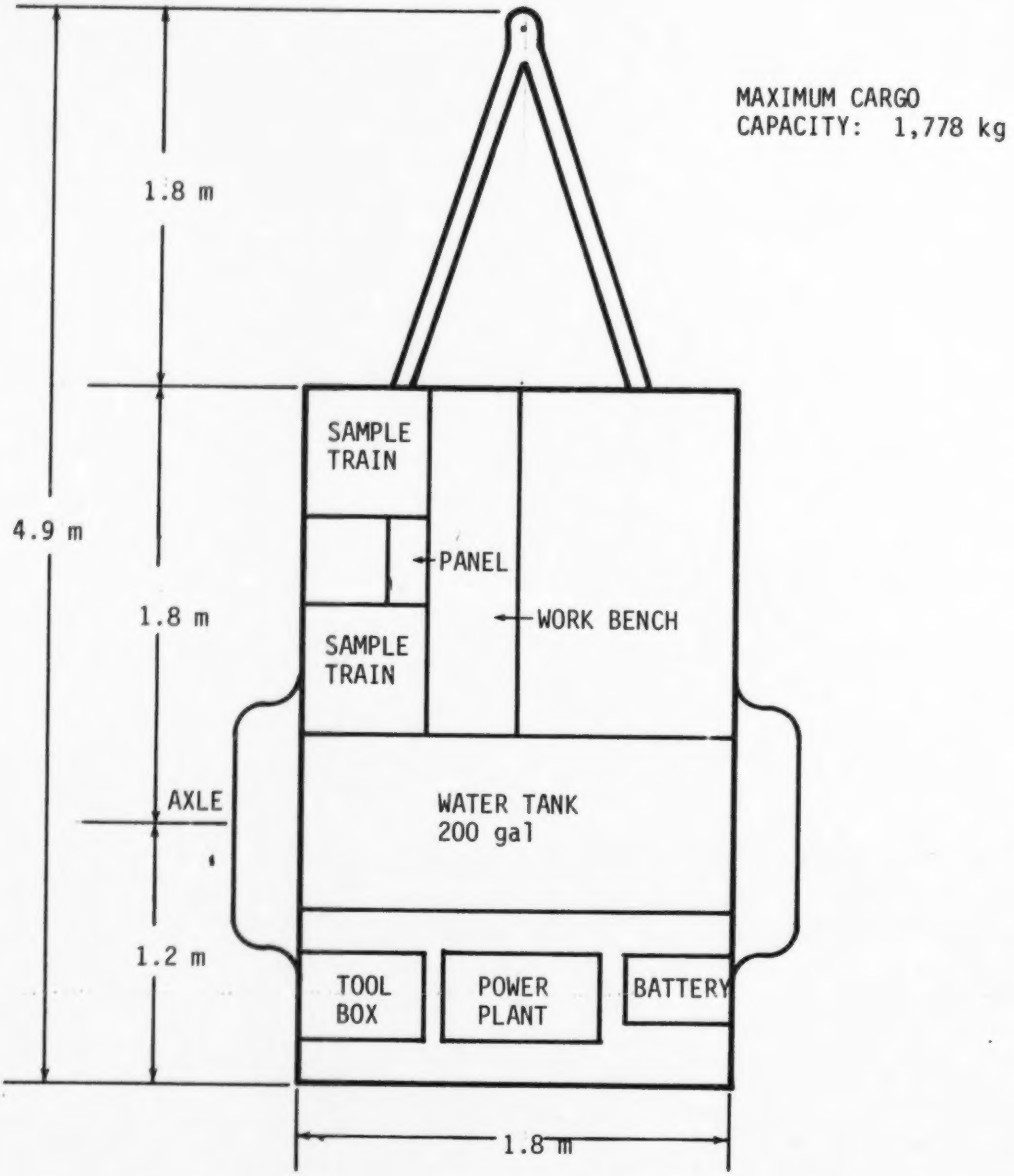

MAXIMUM CARGO
CAPACITY: 1,778 kg
1.8 m
4.9 m
SAMPLE TRAIN
PANEL
1.8 m
WORK BENCH
SAMPLE TRAIN
AXLE
WATER TANK
200 gal
1.2 m
TOOL BOX
POWER PLANT
BATTERY
1.8 m

Figure 34. Plan view of the sampling platform.

Section 6

ROAD TESTS

GUTTER BROOM HOOD

Observation of street sweeper operation clearly showed that gutter brooms and leakage from the "pickup hood" were the major sources of inhalable emissions from the regenerative vacuum sweeper. These emissions need to be contained to prevent dispersion into the air. The approach used in the present study was to enclose the brooms with hoods and to increase the suction in the pickup hood.

It was necessary to develop a hood arrangement that allowed normal broom operations and also reduced fugitive broom emissions to an acceptable level. In the first design, the upper half of the broom was wrapped with rubber sheets. Air in the enclosed broom was vented through the top and into the hopper. Road tests of this hood showed that it had poor containment efficiency. Dust clouds in the gutter broom areas were still visible. This hood was subsequently abandoned in favor of a new abbreviated hood.

In the new design, the gutter brooms were not completely enclosed. A curved, tapered rectangular duct was wrapped around the forward portion of the broom. The duct was similiar to an air curtain distribution manifold and had a 2.5 cm (1 in) wide slot facing the street. The slot was positioned 5 cm (2 in.) above the street and was slightly offset so that it did not scrape the road surface when sweeping an uneven street or hit the curb when the broom was brushing the curb side. This hood operates with a high velocity suction airflow similar to a vacuum cleaner, and also uses the interaction of the rotating broom and street dirt to capture dust. The captured dust is conveyed to the main hopper with piping and 15 cm I.D. flexible hose. A damper valve in the pipe section controls the air-flow from the hood to the hopper.

The sweeper with the new vacuum hood was tested on a commercial street. Visual observations indicated that the hoods performed satisfactorily with the damper valve fully open. No dust cloud was visible in the gutter broom area. However, the hoods were found to be too efficient in picking up street dust. The hood picked up inhalable particles as well as sand. In about 5 minutes, the 15 cm I.D. hose between the hood and the hopper was clogged with about 36 kg (80 lb) of dust.

Since large particles such as sand will be picked up by the pickup hood of the sweeper, the gutter broom hood should only collect inhalable particles. The slot width on the gutter broom hood was subsequently reduced to 1.3 cm (0.5 in) and the air flow was also reduced so that the hood can accomplish its primary objective, i.e. to collect inhalable particles existing in the gutter broom area and convey the particles to the hopper. The modified gutter broom hood was observed to perform properly.

The minimum volumetric air flow rate required for the gutter broom hood to eliminate a dust cloud was measured. This was done by first operating the hood at maximum air flow rate, then gradually reducing the air flow rate until a dust cloud was observed to emerge in the gutter broom area. This flow rate was measured and defined the minimum air flow rate for proper gutter broom hood operation. It was found that the minimum air flow rate for each gutter broom hood is 0.17 m^3/s (350 acfm) or about 7 to 9% of the total air flow of the sweeper.

VENT AIR RATE

The regenerative air flow of the modified sweeper is shown in Figure 35. Under normal sweeping conditions (with the leaf bleeder valve shut) the air from the pressure hose picks up street debris and returns to the hopper. When the pickup head travels on uneven street surfaces, dust puffs emerge out of the pickup head. These dust puffs are eliminated by opening the leaf bleeder valve. This decreases the pressure on the pressure side of the blower and increases the suction in the hopper. As a result, air from the atmosphere flows into the pickup head, elim-

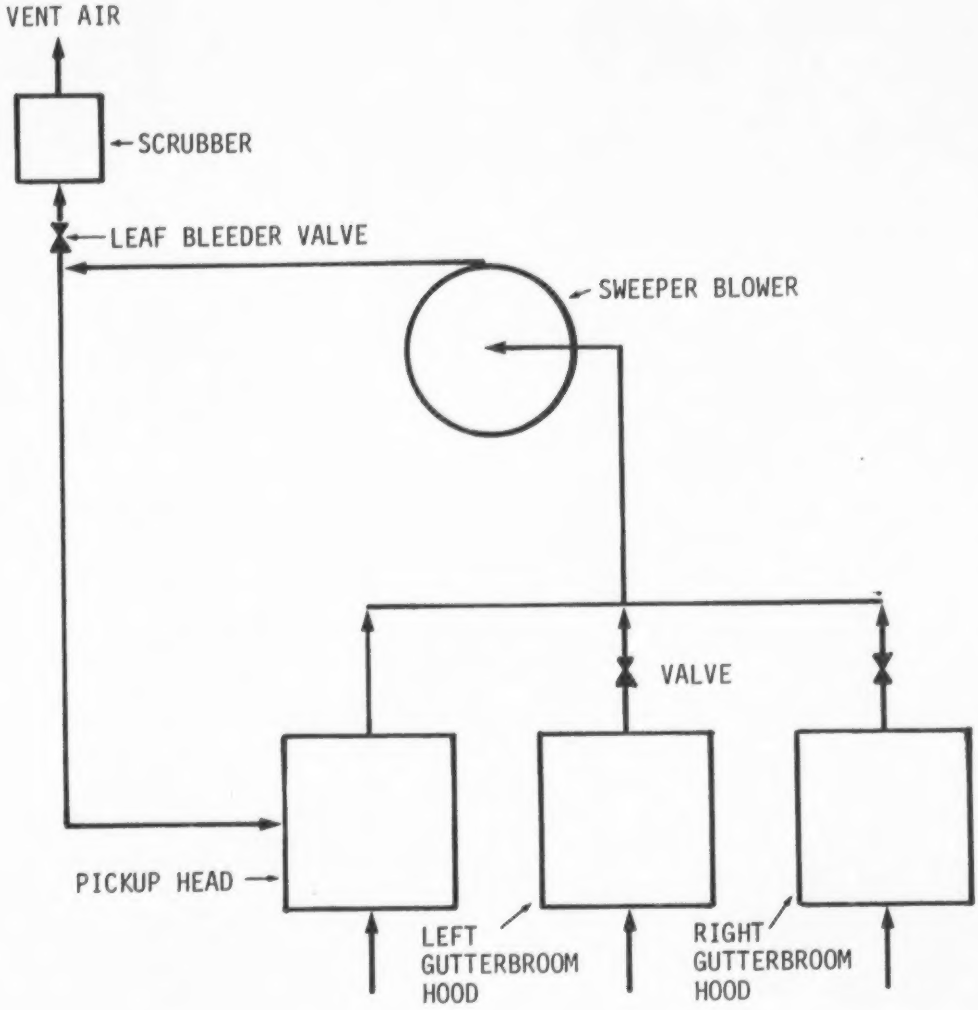

VENT AIR
SCRUBBER
LEAF BLEEDER VALVE
SWEEPER BLOWER
VALVE
PICKUP HEAD
LEFT GUTTERBROOM HOOD
RIGHT GUTTERBROOM HOOD

Figure 35. Schematic diagram of street sweeper flow circuit.

inating the dust puffs. The vent air is cleaned by the scrubber before it escapes into the atmosphere.

To minimize the operating cost and water consumption, the air flow to be vented through the scrubber should be kept at a minimum. However, the air flow should not be so low that dust puffs occur around the gutter broom and the pickup head.

The minimum air flow needed to be vented through the scrubber to prevent the occurance of dust puffs was determined with the gutter broom hood air flow either on or off. The experimental procedures with the gutter broom hoods off are as follows:

1. Close the damper in the hose connecting the gutter broom hood and the hopper.
2. Set and maintain the auxiliary engine (the one which runs the blower, the water pump, and the hydraulics) at a specific speed.
3. Open the damper fully in the duct to the scrubber so that air is vented through the scrubber.
4. Gradually close the damper to reduce the air flow until dust puffs are observed to occur in the pickup head area.
5. Measure the air flow at which dust puffs first occur. This is the minimum air flow needed to be vented.
6. Repeat the above procedures for other engine speeds.

Similar procedures were used when the gutter broom hoods were turned on. The air flow in each hood was maintained at 0.17 m^3/s (350 cfm), which is the minimum required flow for satisfactory hood operation.

It was found that the minimum air flow to be vented through the scrubber with the gutter broom hoods OFF was about 0.33 m^3/s (700 acfm), and about 0.38 m^3/s (800 acfm) with the gutter broom hoods ON.

PARTICLE SIZE DISTRIBUTION AND CONCENTRATION AT SCRUBBER INLET

The spray scrubber was designed for removing particles having a mass median diameter of 4.0 μmA and a geometric standard deviation of 2.0. This size distribution was determined with a cascade impactor located underneath the street sweeper. The particle size distribution might be different at the spray scrubber inlet. Therefore, additional sampling was done at the scrubber inlet to characterize the particles to be cleaned by the scrubber. Streets were chosen with differing activities in the San Diego and Los Angeles areas. This sampling was done before the scrubber was installed, so that scrubber efficiency for these runs was not measured.

Figures 36 through 41 show the results obtained in the San Diego area. Particles from residential areas are larger than the assumed distribution. Particles from an industrial district have distributions close to design condition; particles from commercial district have more small particles than assumed.

Twelve sampling runs were done in the Los Angeles area and results are summarized in Table 13. Figures 42 and 43 show the cumulative mass concentration and particle size distribution, respectively. The concentration and particle size distribution vary greatly from location to location. The sampling results agree with visual observations in that dirtier streets resulted in higher particle concentration and larger particles.

The air flow rate vented through the scrubber has great effects on particle size distribution and concentration. Based on results of experiments performed on the same street, a higher vent flowrate results in a higher particle concentration and larger particles (Figure 44).

The spray scrubber was designed for removing 90% of the particles which have a mass median diameter of 4.0 μmA and a geometric standard deviation of 2.0. A more efficient spray scrubber is probably needed. There are more submicron particles in the air stream at the scrubber inlet than assumed.

Street samples collected indicate a difference in characteristic size dirt when neighborhoods are considered. The major

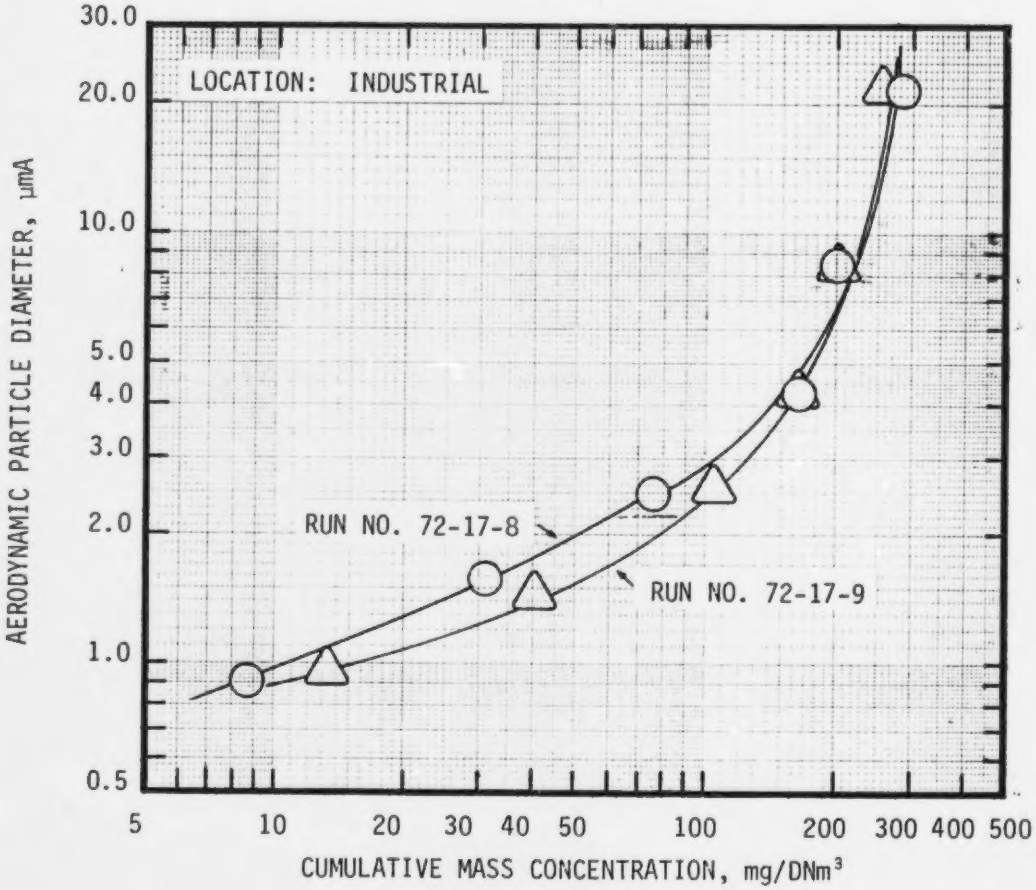


Figure 36. Particle size vs. mass concentration of dust at scrubber inlet in an industrial area.

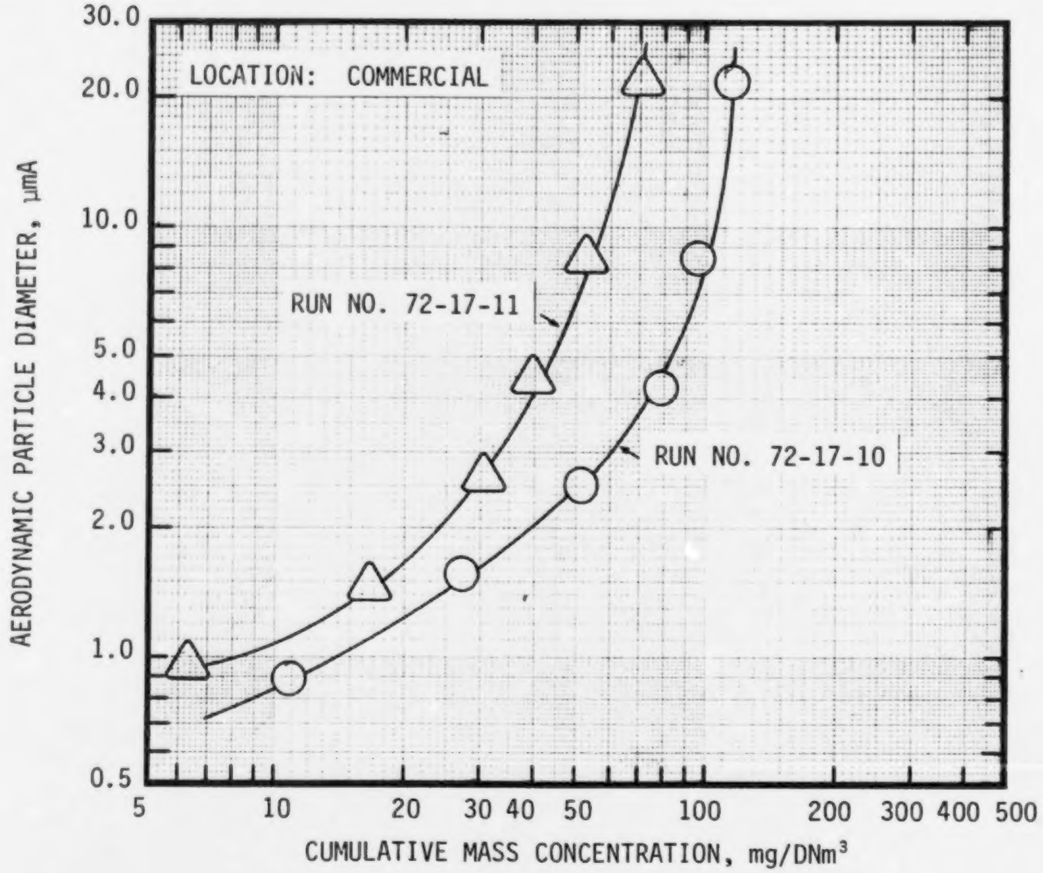


Figure 37. Particle size vs. mass concentration of dust at scrubber inlet in a commercial area.

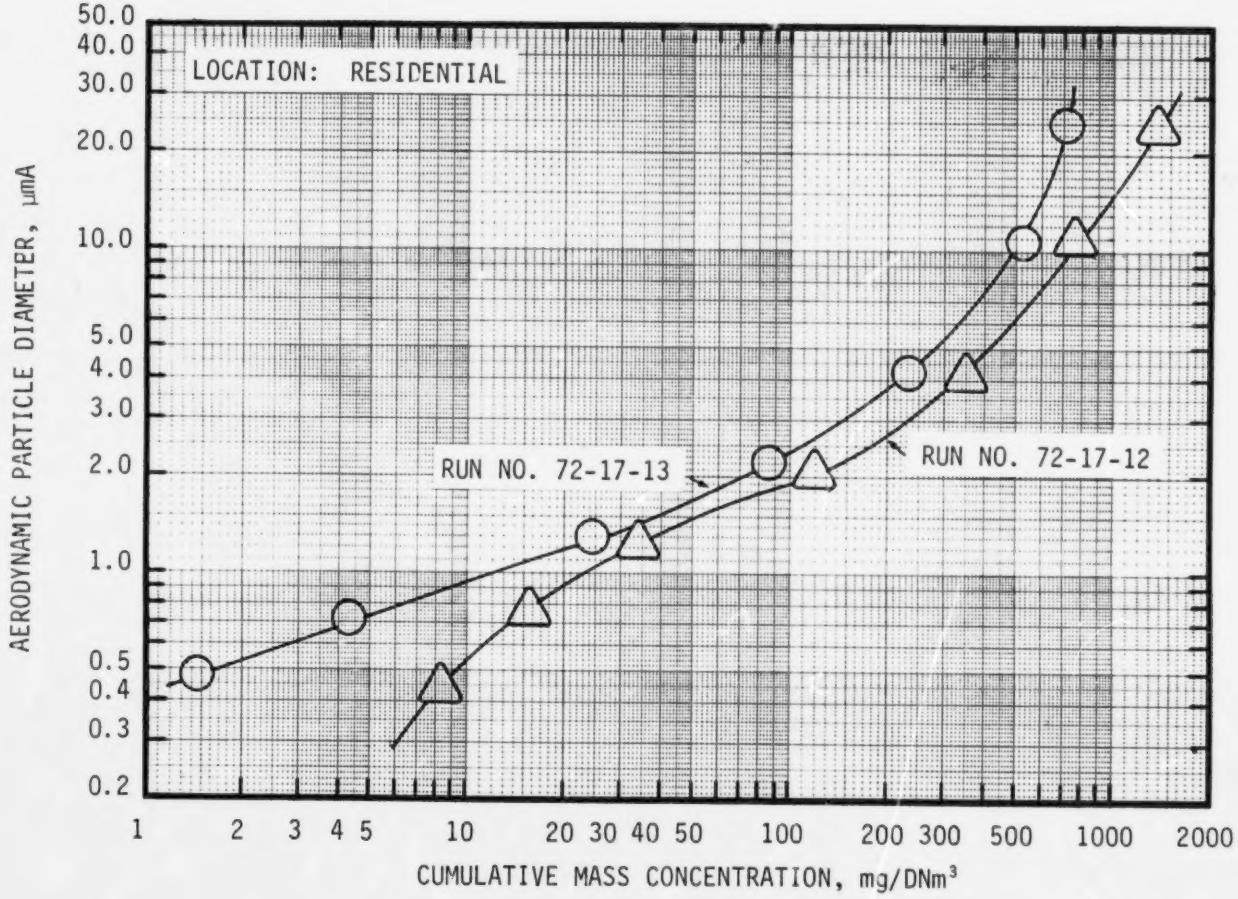


Figure 38. Particle size vs. mass concentration of dust at scrubber inlet in a residential area.

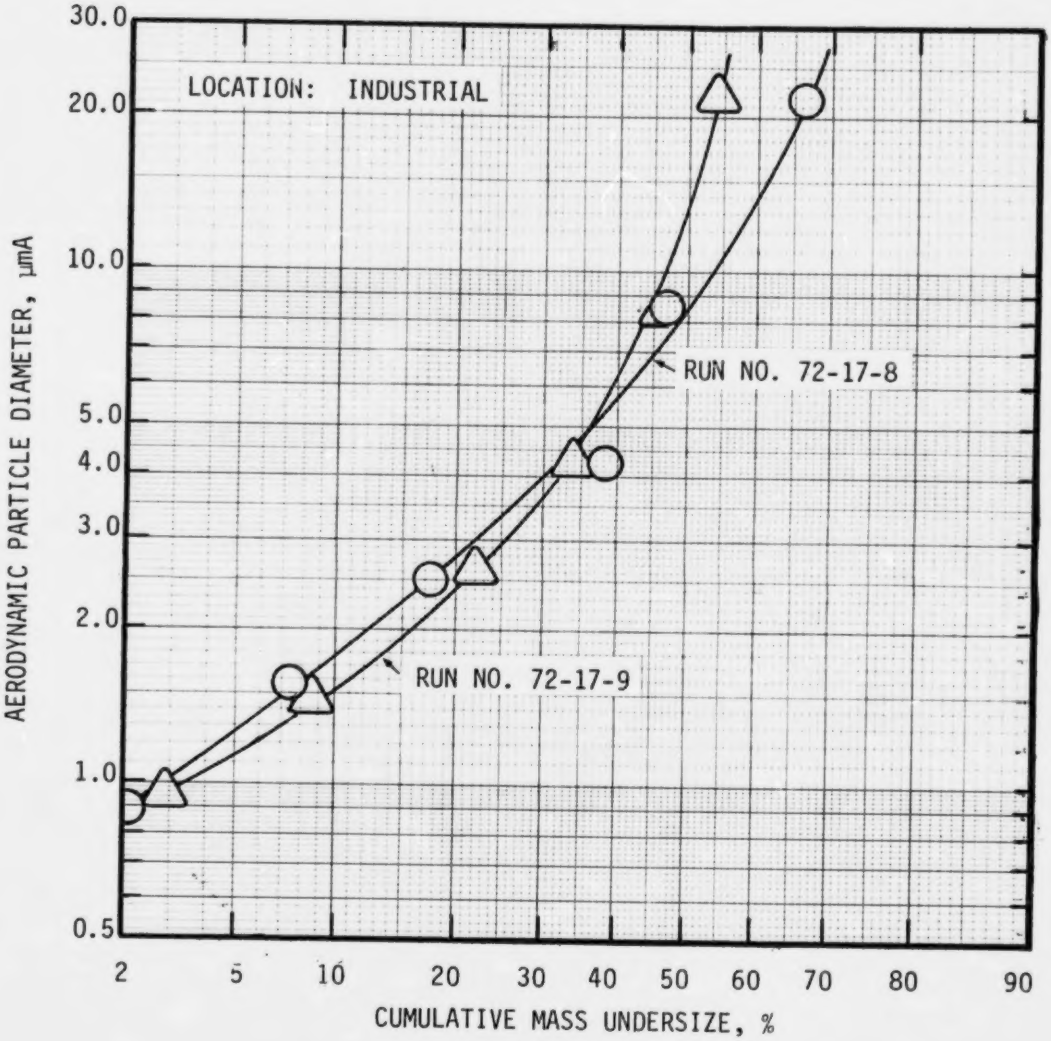


Figure 39. Particle size distribution of dust at scrubber inlet in an industrial area.

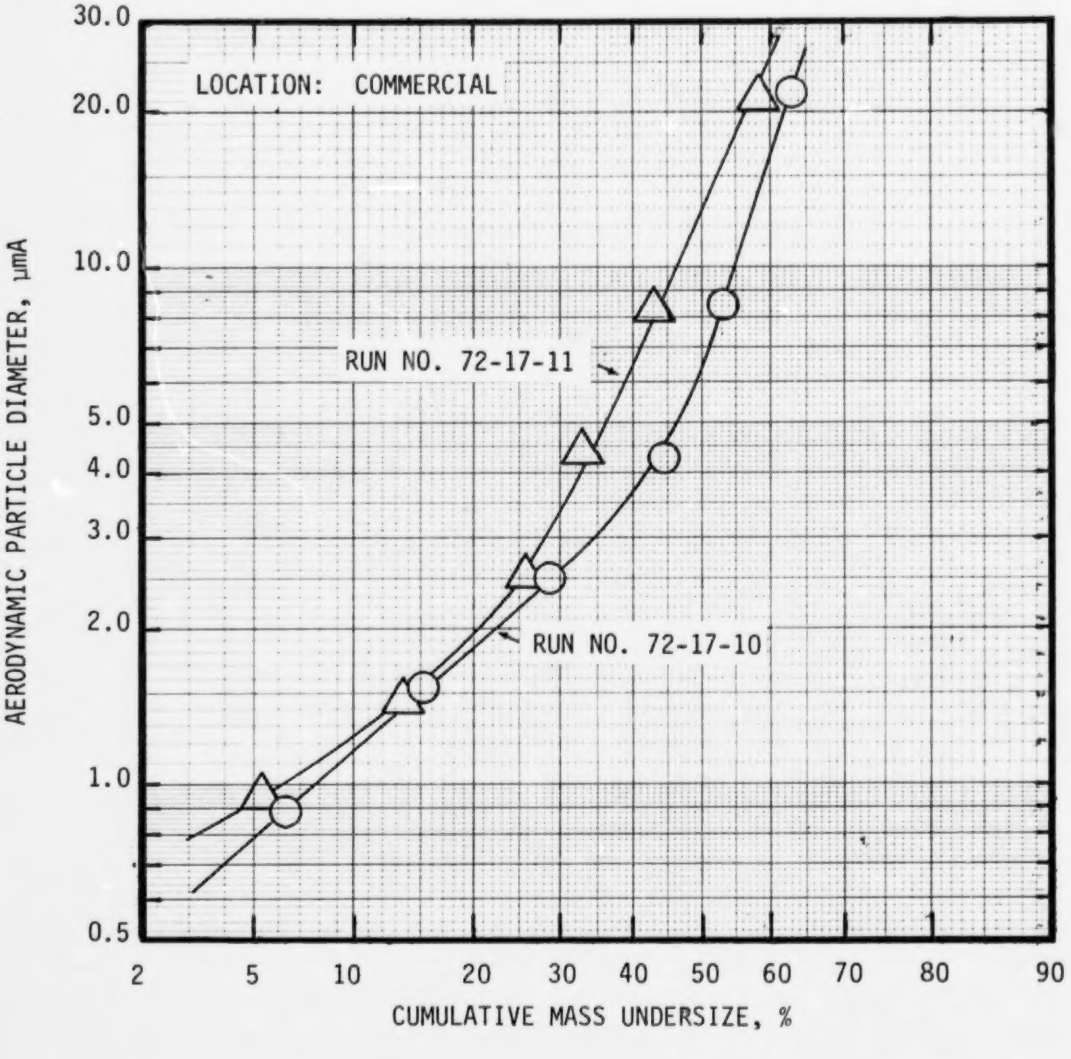


Figure 40. Particle size distribution of dust at scrubber inlet in a commercial area.

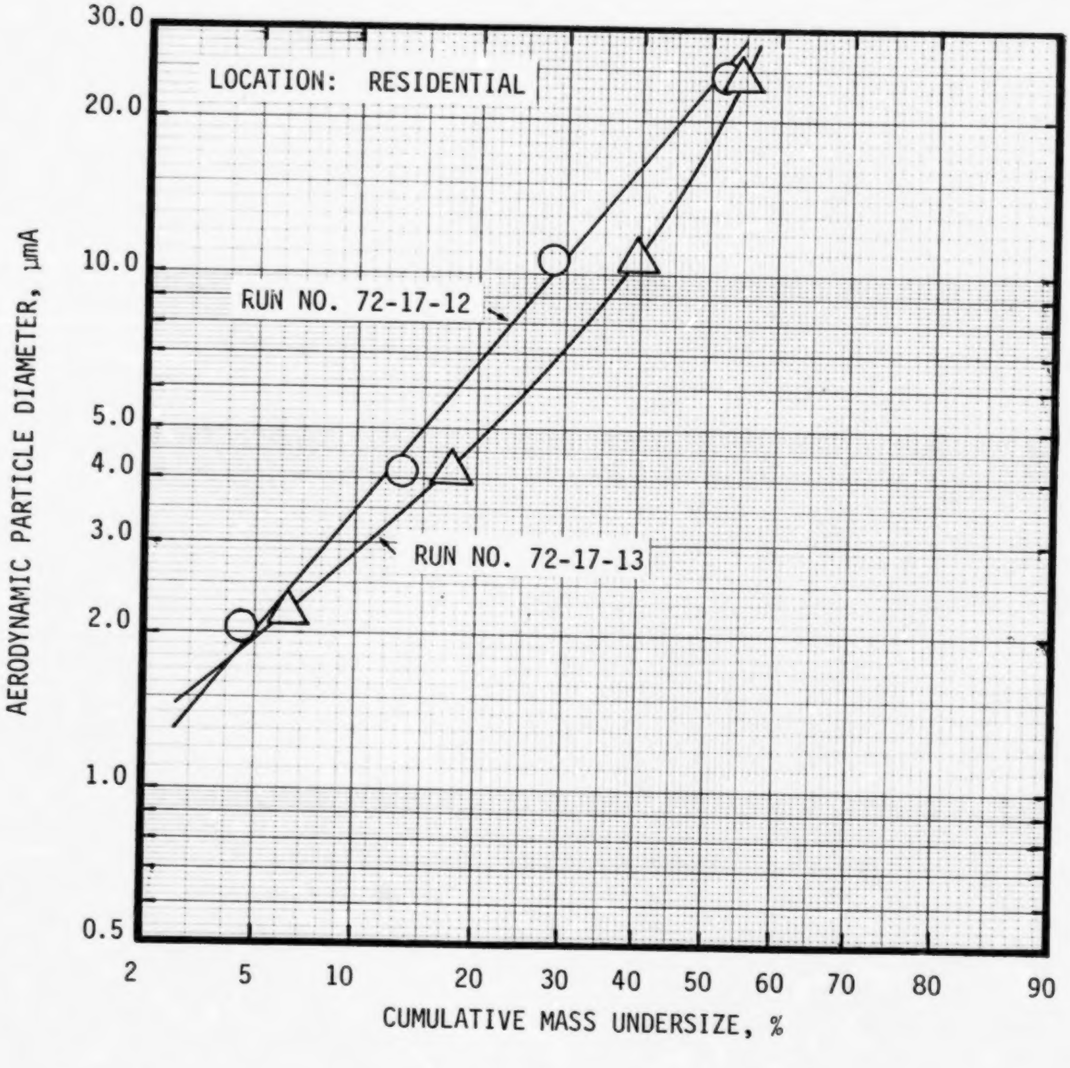


Figure 41. Particle size distribution at scrubber inlet in a residential area.

TABLE 13. SUMMARY OF SAMPLING RESULTS FROM LOS ANGELES AREA

Run Number Symbol	Location (L. A. Area)	Industry	Traffic Conditions	Scrubber Flow Rate Am^3/min	Total Mass Concentration mg/DNm^3	Mass Median Diameter µmA	Geometric Standard Deviation σ_g	Comments
18/5	Carson	Texaco Refinery	Medium-heavy	20	3,190	10.0	4.5	Heavy street loading
18/6	Wilmington	Bridge on Anaheim Street	Very heavy	20	770	5.2	3.5	Heavy street loading
18/7	Torrance	U.S. Steel	Light-medium	32	3,503	26	15.3	Heavy street loading. U.S. Steel plant was in the process of being demolished.
18/8	Torrance	Mobil Refinery	Heavy	32	684	65	8.1	Medium street loading
18/9	Torrance	Coke plant	Heavy	32	132	42	7.1	Light-medium street loading opposite Mobil refinery on Crenshaw.
18/10	Torrance	Coke plant	Heavy	32	193	100	8.7	Light-medium street loading past the truck exit from the Coke plant. Coke visible on the street.
18/11, 12	Torrance	U.S.	Light-medium	20	386	7.7	7.0	Heavy street loading same street as Run 18.7. Run w/street sweeper efficiency test 18/12.

TABLE 13. CONTINUED

Run Number Symbol	Location (L. A. Area)	Industry	Traffic Conditions	Scrubber Flow Rate ACFM	Total Mass Concentration mg/DNm³	Mass Median Diameter µmA	Geometric Standard Deviation σ_g	Comments
18/13	Vernon	Bethlehem Steel	Medium	710	265	17.5	4.9	Medium street loading
18/14	Vernon	Bethlehem Steel	Medium-heavy	710	362	13.1	5.0	Medium street loading
18/15	Vernon	Warehouse and steel plant	Medium	710	134	15.4	4.3	Medium street loading
18/16	Vernon	Grain mill	Heavy	1,130	556	170	9.4	Medium-heavy street loading
18/17	Vernon	Jorgenson	Medium	1,130	2,186	47	5.4	Heavy street loading run w/street sweeper efficiency test 18/17

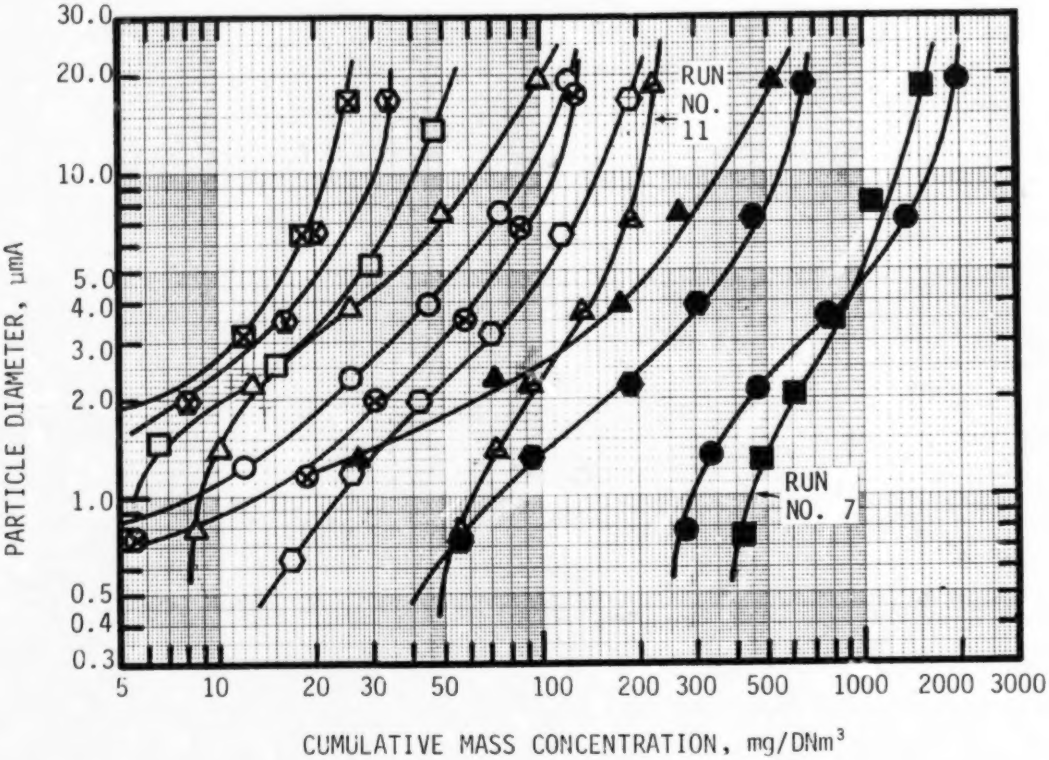


Figure 42. Scrubber inlet dust concentration.

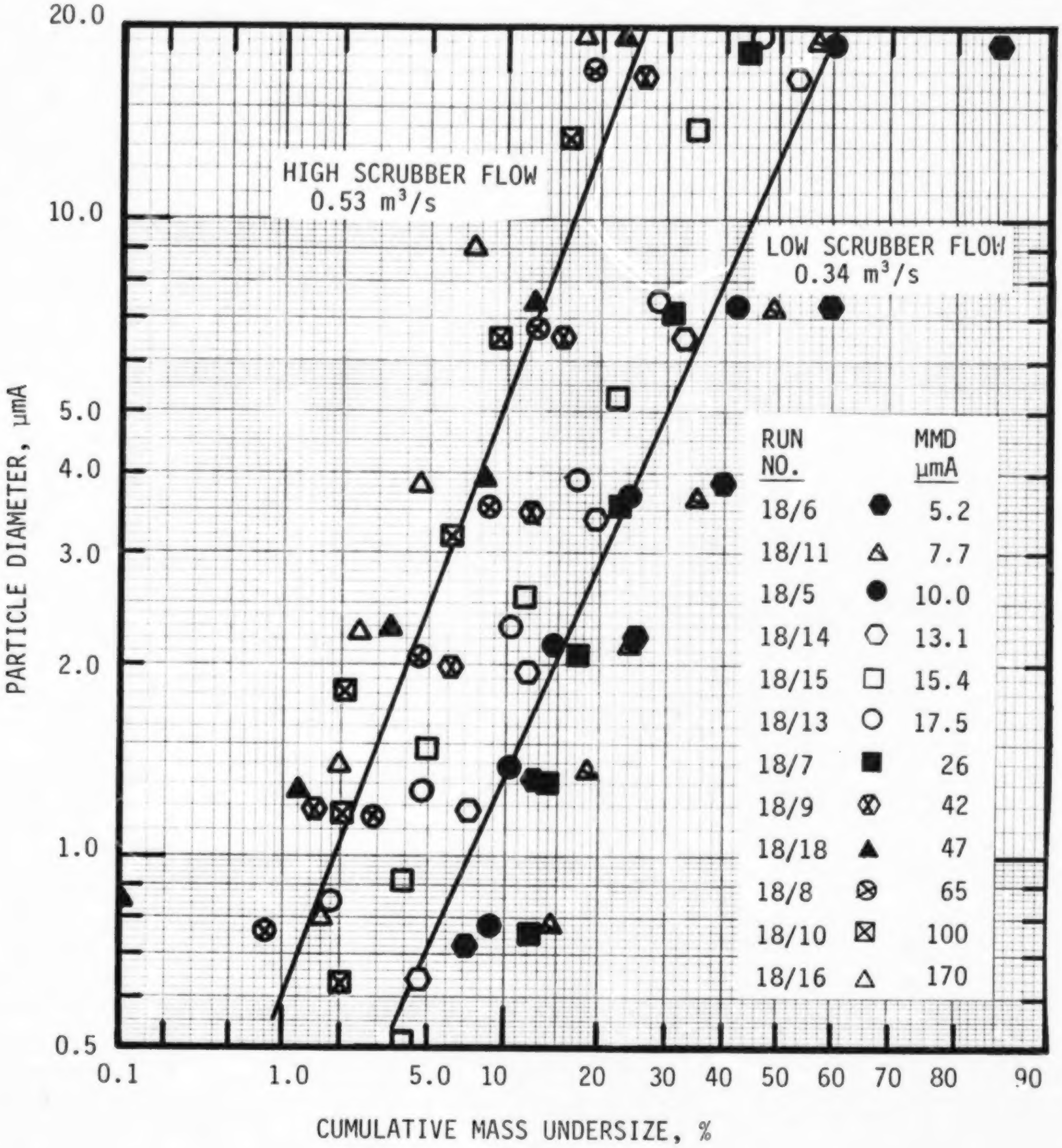


Figure 43. Particle size distribution.

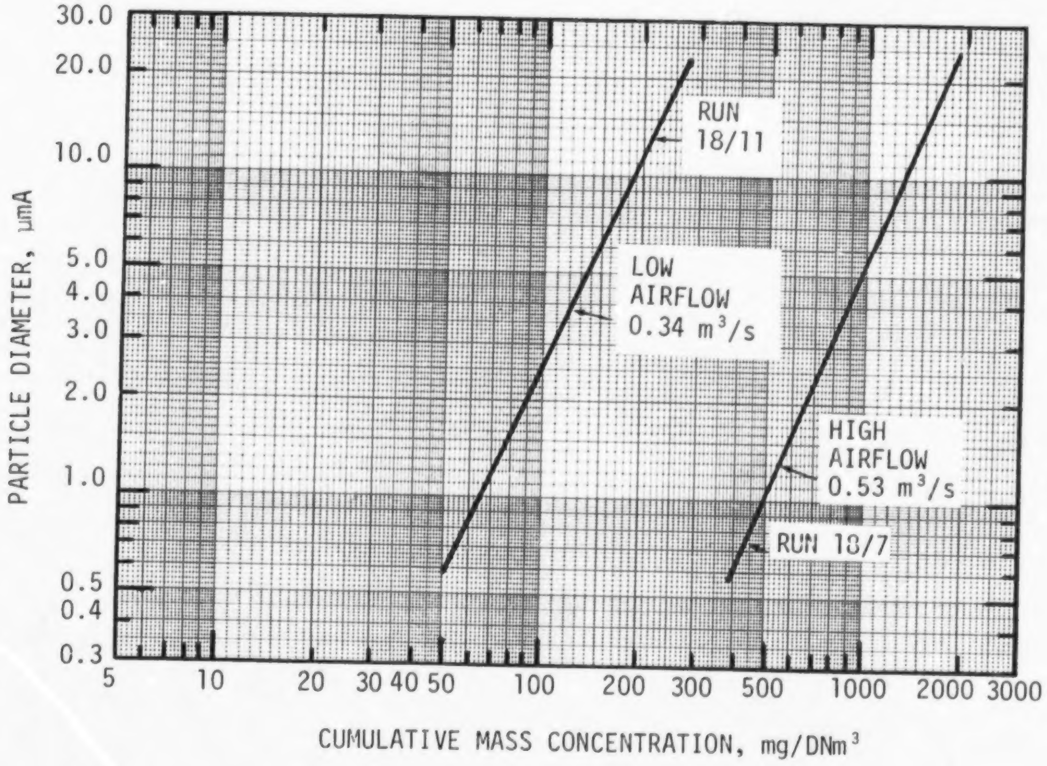


Figure 44. Effect of vent air flow on scrubber inlet dust concentration.

distinction noticed between neighborhoods is the amount of traffic; street dirt is reduced in size by continuous traffic.

SWEEPING EFFICIENCY

Street Dust Measurement Method

To determine the sweeping efficiency of the modified sweeper, a method is needed which measures the amount of dust that can be dispersed into the ambient air by the mechanisms actually occuring on streets. The mechanisms of street dust removal are (Brookman and Martin, 1979):

1. Reentrainment (by air currents around moving vehicles).
2. Wind erosion (similar to 1, but due to natural air currents).
3. Displacement (similar to 1, re-disposition near street).
4. Rainfall runoff.
5. Street cleaning.

The first three mechanisms result in airborne dispersal of street dirt, so the sampling method should measure the amount of inhalable particulate matter which can be dispersed by these.

Preliminary experiments were performed to measure street dust density with a brush-type vacuum cleaner, as has been done by Dahir and Meyer (1974). The dust on the street was first loosened with a brush, and then taken up and filtered by the vacuum cleaner. The amount of dust was determined from filter weight gain. Street dust density was calculated by dividing the weight of the dust by the area vacuumed.

This method was found to have several deficiencies. The vacuum cleaner can suck up dust which is deposited deeply in cracks. The dust in cracks is not normally reentrained. Scouring and brushing the street surface to loosen the street dust is not a naturally occuring dust dispersion mechanism. Further, the total amount of dust vacuumed increases with each pass of the vacuum nozzle; therefore, there is no logical end-point for sampling.

Consequently, the above method was abandoned and a new method developed. The new method uses a vacuum cleaner with a modified pickup nozzle. The filter in the vacuum cleaner is a custom-made bag house type filter. Two pickup nozzle designs were evaluated. The first one was of circular design and is shaped to create a uniform 97 m/hr (60 mph) air flow field at the street surface (Figure 45). The dust dislodged by the air flow is sucked into the vacuum and filtered by the vacuum bag. This method simulates dust reentrainment due to air currents around moving vehicles and wind erosion.

A detailed definition of reentrainment would require a complex model of airflow around an automobile. Assuming that the maximum air velocity caused by the passage of an automobile will not exceed its velocity, and that 97 km/hr (60 mph) is a reasonable maximum automobile velocity, the resultant maximum reentrainment velocity would be 97 km/hr.

Wind speeds are generally much less than 97 km/hr (27 m/s), so this velocity is conservatively high to represent the influence of wind erosion.

The displacement mechanism is essentially similar to that for reentrainment, and due to the same vehicular motion. The definition differs in that the particles stay in suspension only long enough to reach the area immediately adjacent to the street. An air velocity of 97 km/hr would adequately represent this vehicle-induced mechanism.

Figure 46 shows a sketch of the second pickup nozzle design. The nozzle had an adjustable inlet air jet. The air jet was designed to aim the jet at the street surface in such a manner so as to maximize the dust reentrainment in the air flow.

The inlet jet angle may influence the particle size and concentration of the reentrained dust, so they are measured for jet angles of 0°, 45°, and 90° (defined as "0"in Figure 47). Particle size distribution and concentration of the reentrained dust were measured at the vacuum hose with cascade impactors. Figure 47 shows the results.

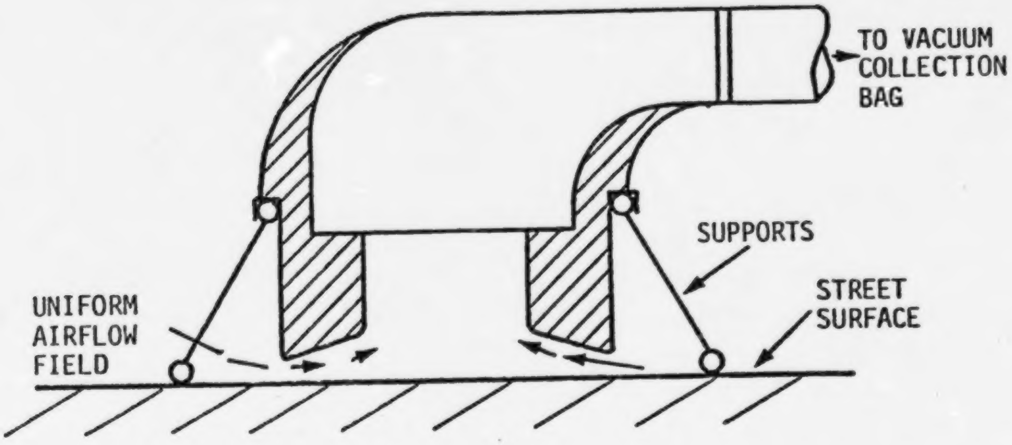

TO VACUUM COLLECTION BAG
SUPPORTS
STREET SURFACE
UNIFORM AIRFLOW FIELD

Figure 45. Uniform Airflow Vacuum Nozzle.

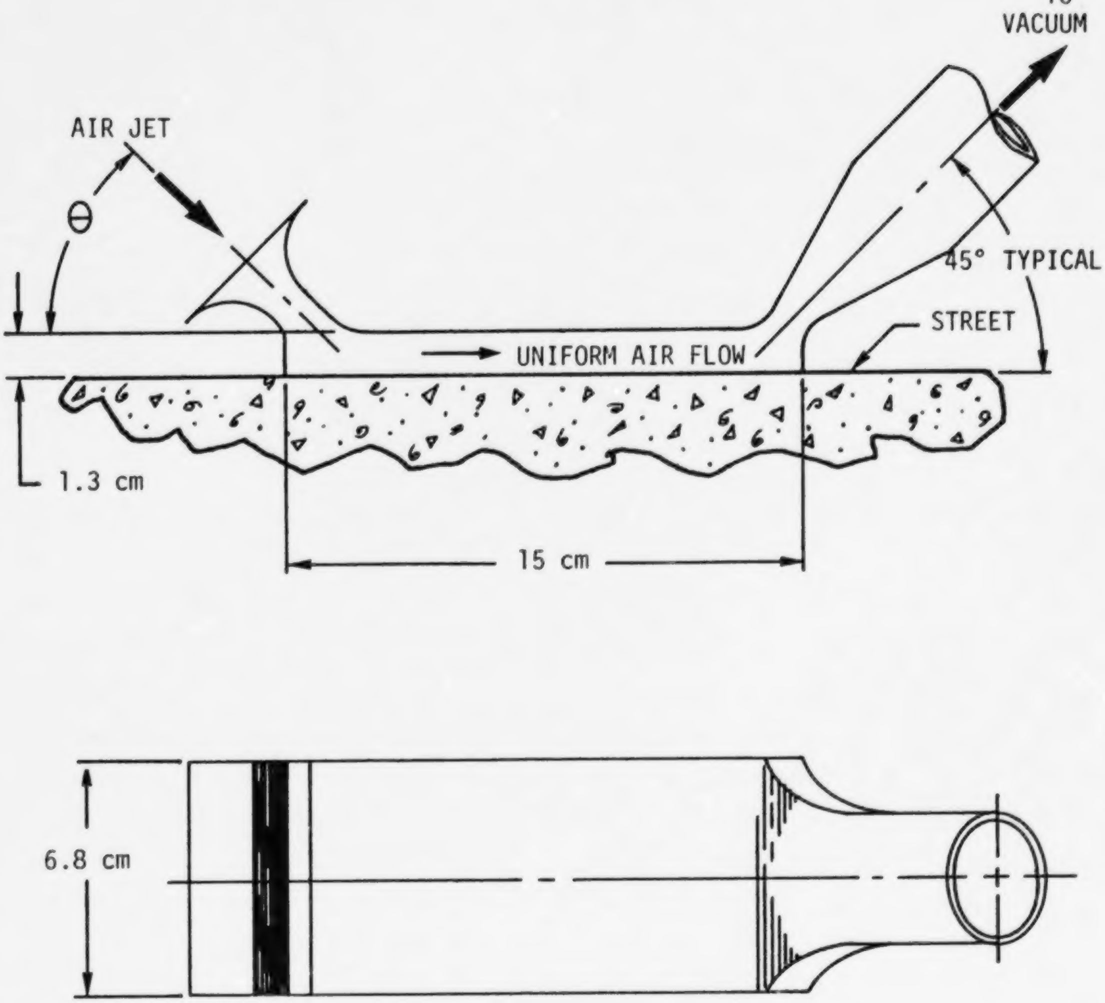

TO VACUUM
AIR JET
Θ
45° TYPICAL
STREET
UNIFORM AIR FLOW
1.3 cm
15 cm
6.8 cm

Figure 46. Air Jet Nozzle

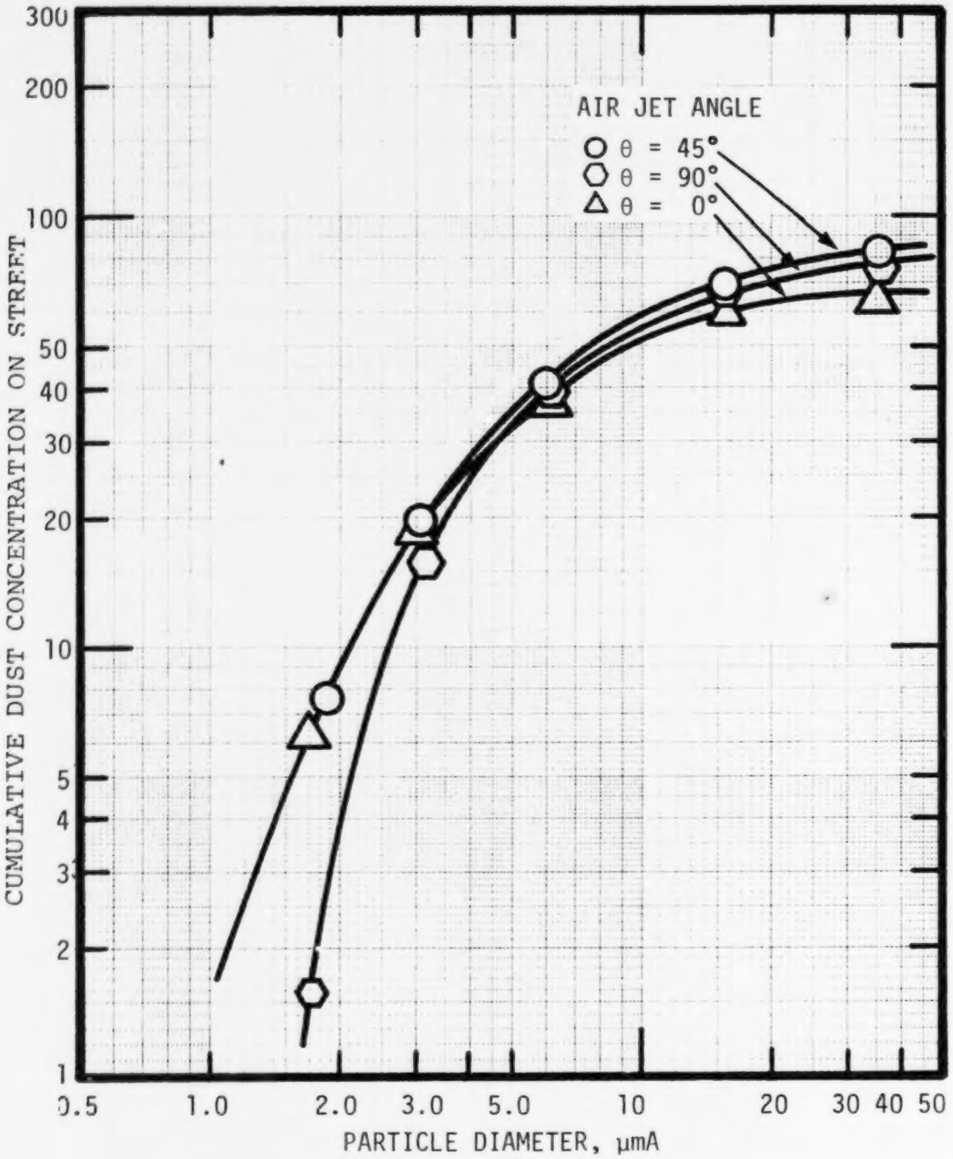


Figure 47. Air jet nozzle performance.

The 0° position produced a lower mass concentration and larger particles than did the 45° or 90° positions. This could be due to the air flow being parallel to the street surface at 0° position which does not reentrain dust deposited in crevices. At other jet angles, the jet stream impinges on the street surface. Dust deposited in the crevices is blown out and reentrained by the jet stream.

An inlet jet angle of 45° yielded maximum dust concentration. Therefore, in street sweeping efficiency measurements, the inlet angle of the jet nozzle was set at 45°.

Both nozzles yielded satisfactory results and both were used in street sweeping efficiency determinations.

Street Sweeping Efficiency Measurement

Street sweeping efficiency is determined by measuring the street dust concentrations before and after sweeping. The street was divided into sections of equal area for dust concentration measurements. Each section was further sub-divided into the gutter broom area and the pick-up head area as shown in Figure 48. The equal area sections are used to reduce the effect of localized differences in the street dirt loading. Each "before" and adjacent "after" section has dirt loading representative of that local area, and will give accurate street cleaning data. The sub-division into gutter broom and pick-up head strips is for separately measuring the performance of these two street cleaning devices. The gutter area has a higher dirt loading than the street due to traffic and water run-off. Also, the pick-up head uses an air-jet mechanism for cleaning the street, while the gutter broom uses a rotating wire broom. These differences may result in different street sweeping efficiencies for the gutter and street area.

Figures 49 and 50 show plots of street dust density before and after sweeping. Run No. 18/17 was done on a street with on street parking and Run No. 18/12 on a street without parking. Street dust was concentrated in the gutter area. Parked cars increased the dust density.

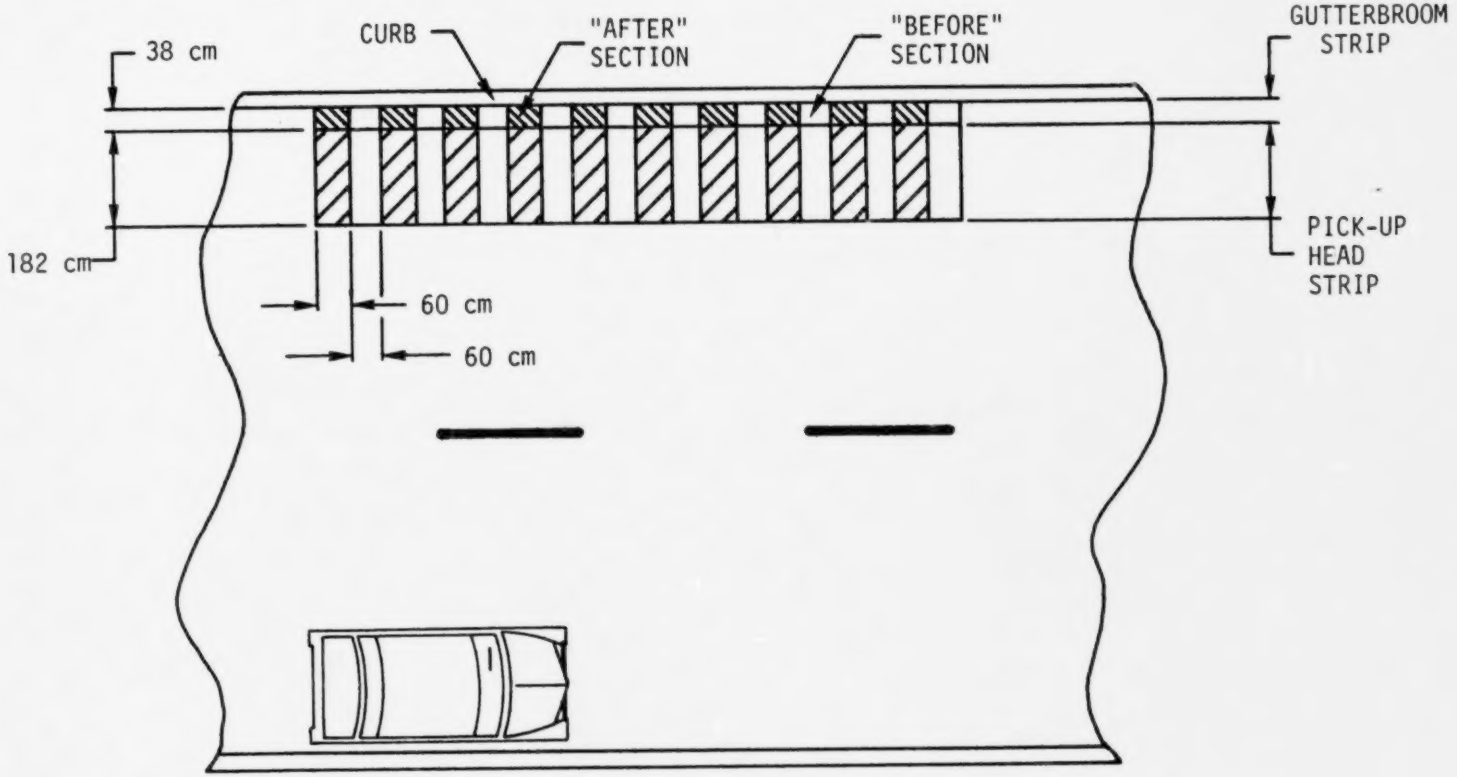

38 cm
CURB
"AFTER" SECTION
"BEFORE" SECTION
GUTTERBROOM STRIP
182 cm
PICK-UP HEAD STRIP
60 cm
60 cm

Figure 48. Test strip layout for street sweeping efficiency measurement.

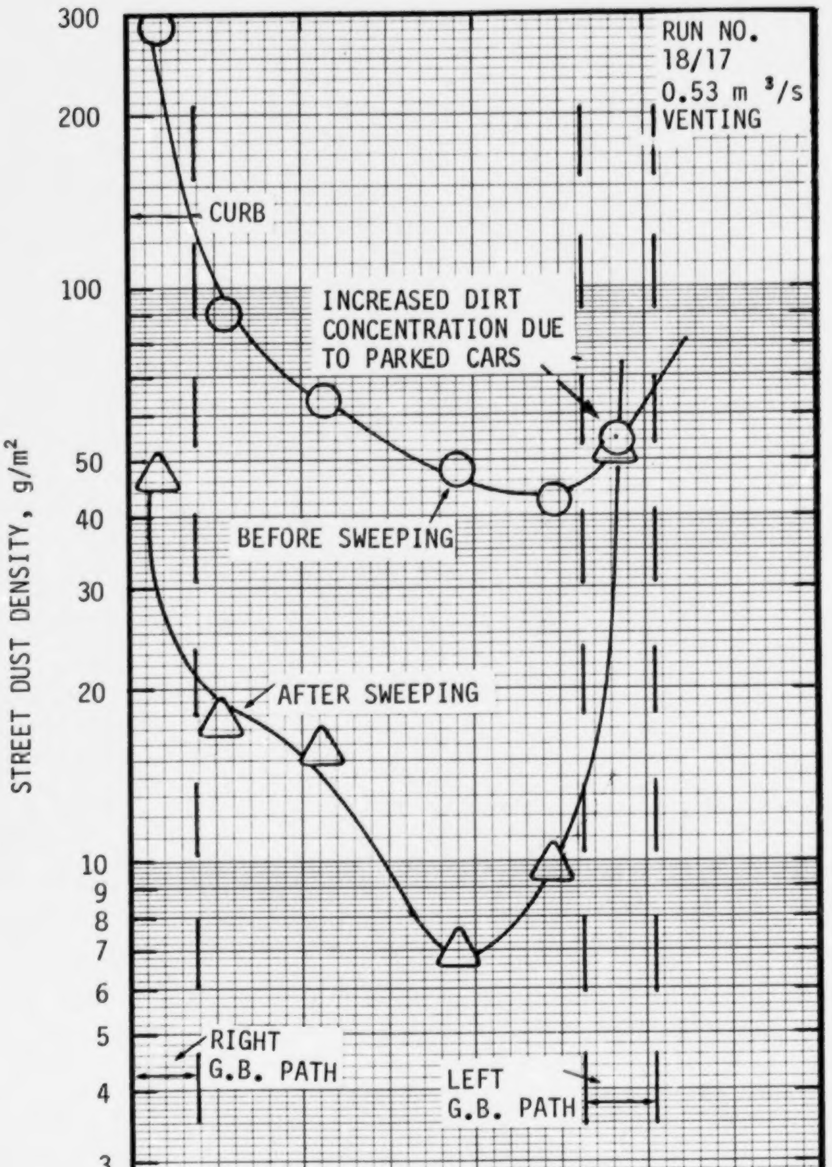


Figure 49. Street dust distribution before and after sweeping. (On street parking)

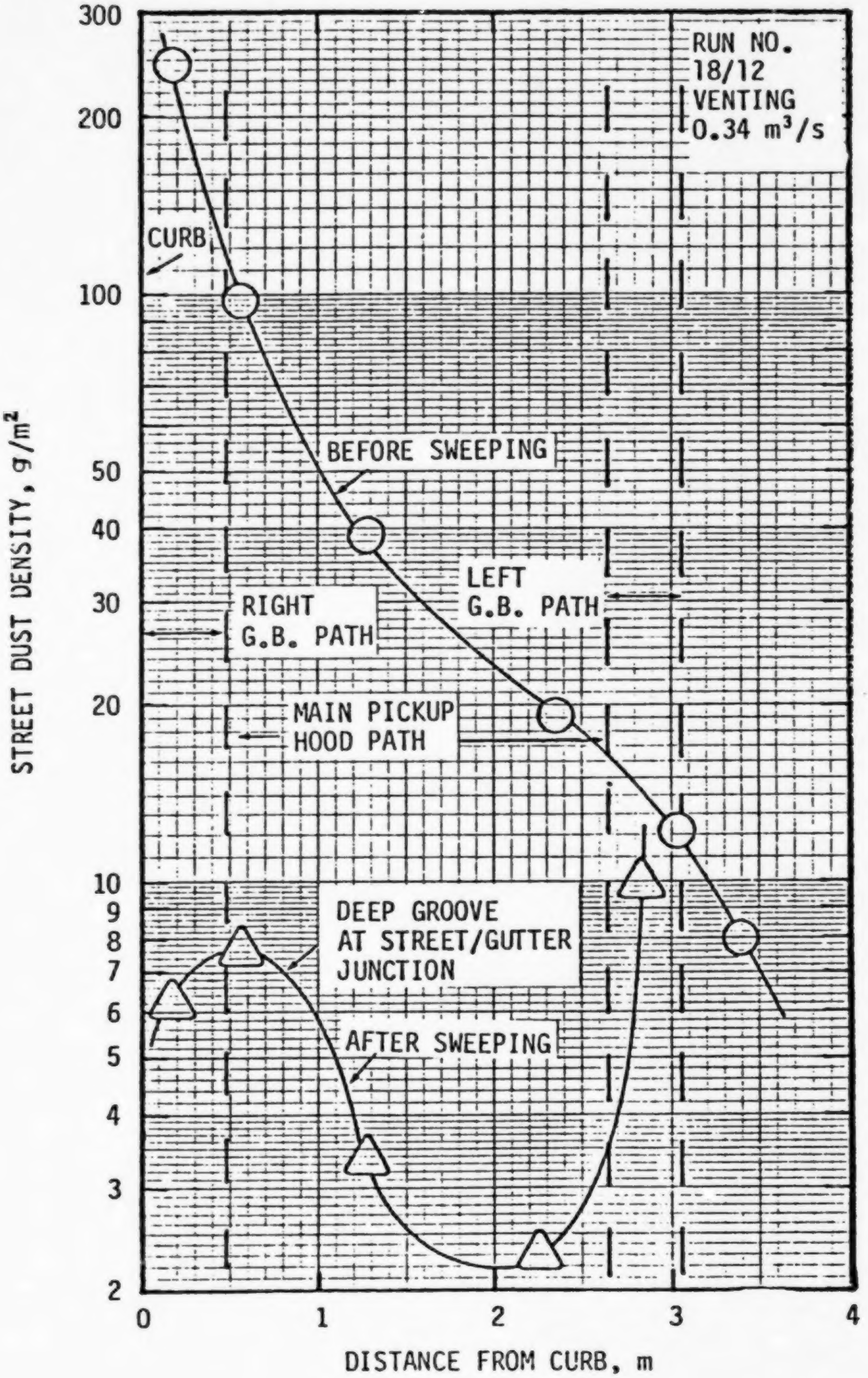


Figure 50. Street dust distribution before and after sweeping.

The street sweeper sweeping efficiency was calculated from the results presented in Figures 49 and 50 and it ranged from 75% to 97%, as seen from Figure 51.

The right hand hood achieved a cleaner street surface than did the left hand hood even though the right hand hood had a higher concentration of dirt to clean. In both experiments, the righthand (curb-side) was maintained at a suction flow rate of 0.27 m^3/s (570 acfm) and the left hand (street side) at 0.7 m^3/s (360 acfm). The curb and gutter were made of concrete, which is smoother than the street surface of asphalt. The dirt is more easily sucked up in the gutter. The higher cleaning efficiency for the curbside broom could be due to a higher air flow rate and different street surface textures.

The fraction of the dust reentrained from the street smaller than 15 μmA was measured. Previous investigators (Sartor and Boyd, 1972) have used wire mesh sieves to separate the street dirt sample into size fractions; but this method has not been proved to be reliable for particles smaller than 45 μm (325 mesh sieve) diameter.

A similar method was tried in this study. A sample of dust was taken from the filter bag of the vacuum and either sieved to obtain the fraction passing a 325 mesh (45 μm opening) screen or wet vacuum filtered to obtain the fraction below 25 μm diameter. This sample was then analyzed for the particle size distribution with a Coulter counter. The particle size distribution determined by this method varied greatly even with samples taken from the same vacuum bag. This indicated that the sample taken was not representative. In addition, the Coulter counter may have broken up the agglomerates. Therefore, this method of determining the sweeper efficiency with respect to particle diameter was abandoned and a cascade impactor was used.

A sample probe was inserted into the vacuum hose (2 1/2" Sch 80 PVC pipe) of the vacuum cleaner to withdraw an isokinetic sample of the air stream. The sample passed through a pre-cutter to remove particles with diameter larger than 35 μmA and a University of Washington cascade impactor for size classifica-

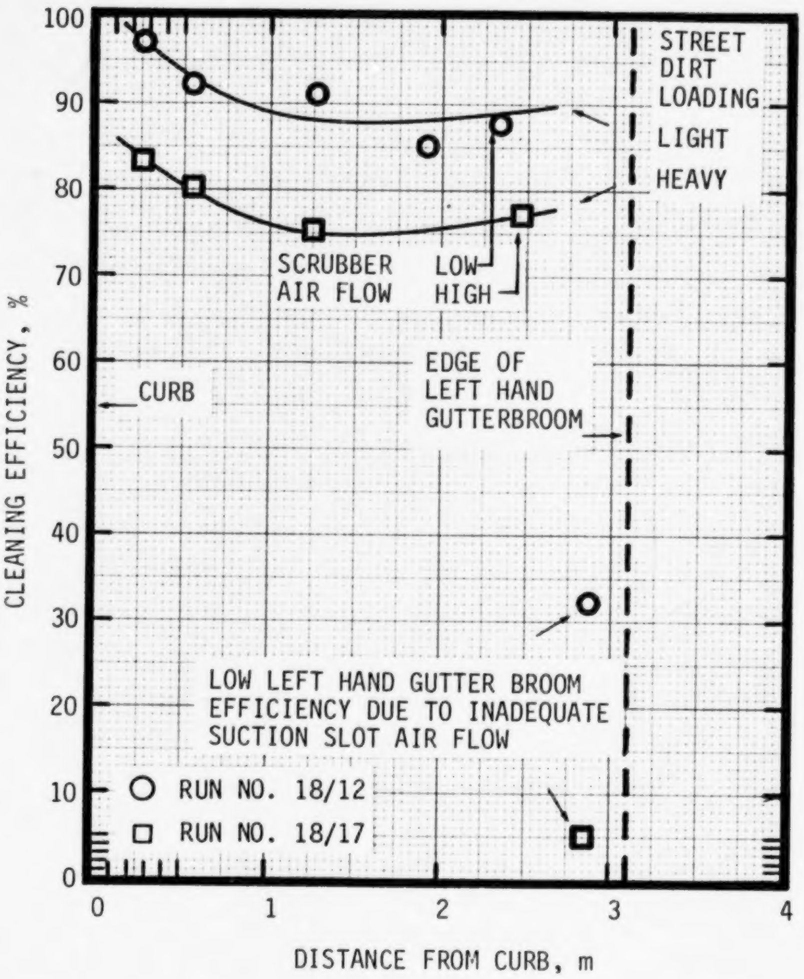


Figure 51. Overall street sweeping efficiency.

tion. The sample flow rate was kept low to fractionate the particles into size ranges from 0.9 to 38 μmA diameter.

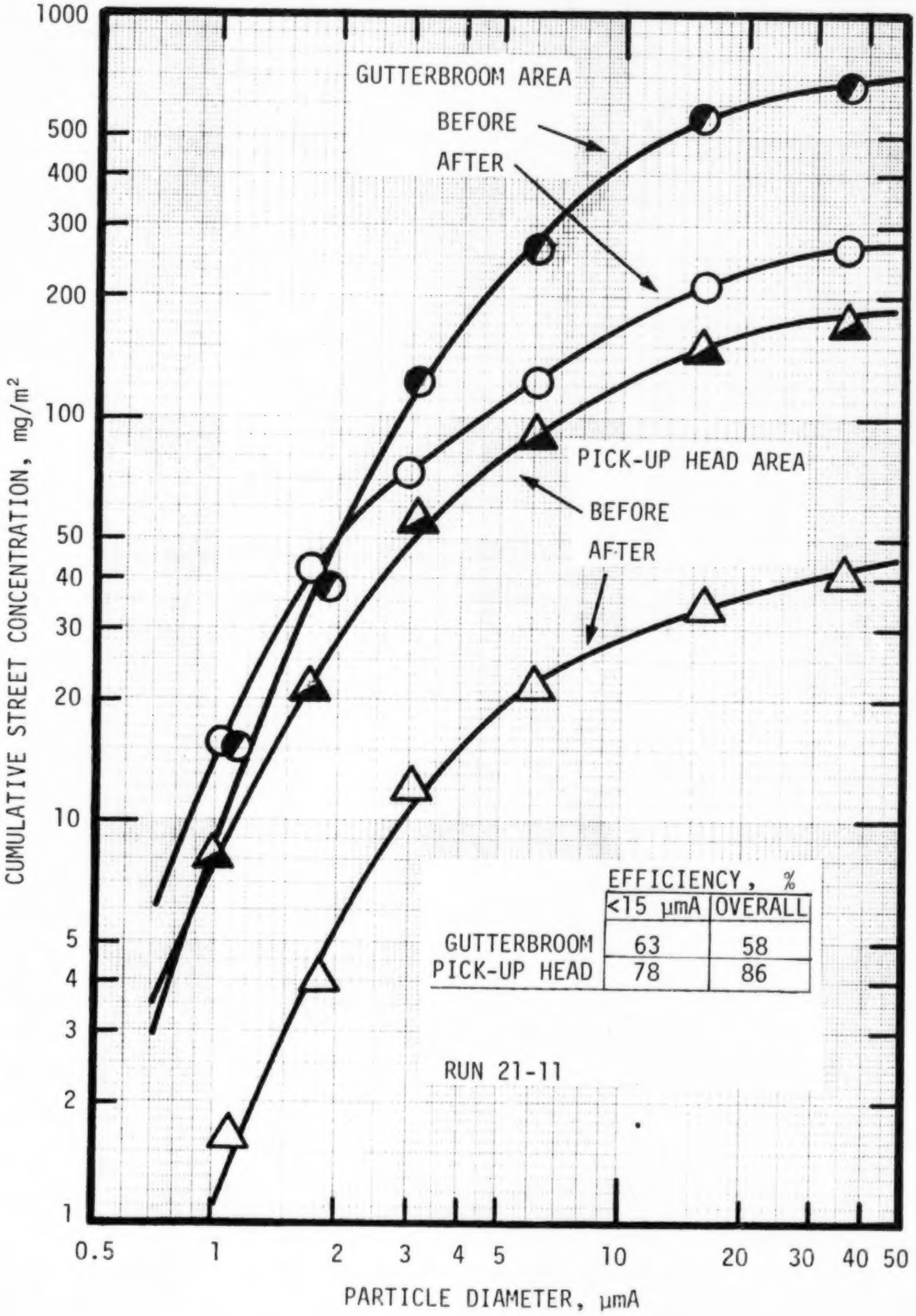
The cumulative concentration of street dust is plotted against aerodynamic particle diameter for before and after street sweeping in Figures 52 and 53. The main pick-up head of the sweeper had a higher sweeping efficiency because it has air jets blasting at the road surface to lift the dust off the street. The gutter broom was not effective in removing street dust less than 2 μmA diameter. It seems that the broom does not impart enough momentum to the smaller particles for them to move over to the pickup head area or to suspend them in the air, and cannot reach into the crevices to stir up the dirt.

The performance of the modified sweeper was compared to that of a regular sweeper visually at a construction site. The modified sweeper not only drastically reduced the dust clouds around the sweeper, it also gave a cleaner street. A cleaner street will reduce the fugitive street dust emission.

The sweeping efficiency of the gutter broom with the hood air flow on and off was measured in a parking lot. The efficiency was 57% with hood vent air flow off and 65% with the air flow on.

SCRUBBER EFFICIENCY

The performance of the spray scrubber was determined in the laboratory by injecting lime dust into the pickup head and simultaneously sampling the scrubber inlet and outlet air streams with cascade impactors. Table 14 shows a summary of the results. Figures 54 through 56 show the experimental grade penetration curves for three scrubber operating conditions. The water and particles were not charged in these experiments because electrostatic augmentation only improves the collection of small particles, and there were not that many small particles in the street dust. It can be seen from the un-charged spray scrubber has adequate collection efficiency at a liquid/gas ratio of 0.68 l/m³ (5.1 gal/mcf) or higher.



	EFFICIENCY, %	
	<15 μmA	OVERALL
GUTTERBROOM	63	58
PICK-UP HEAD	78	86

Figure 52. Street sweeping efficiency.

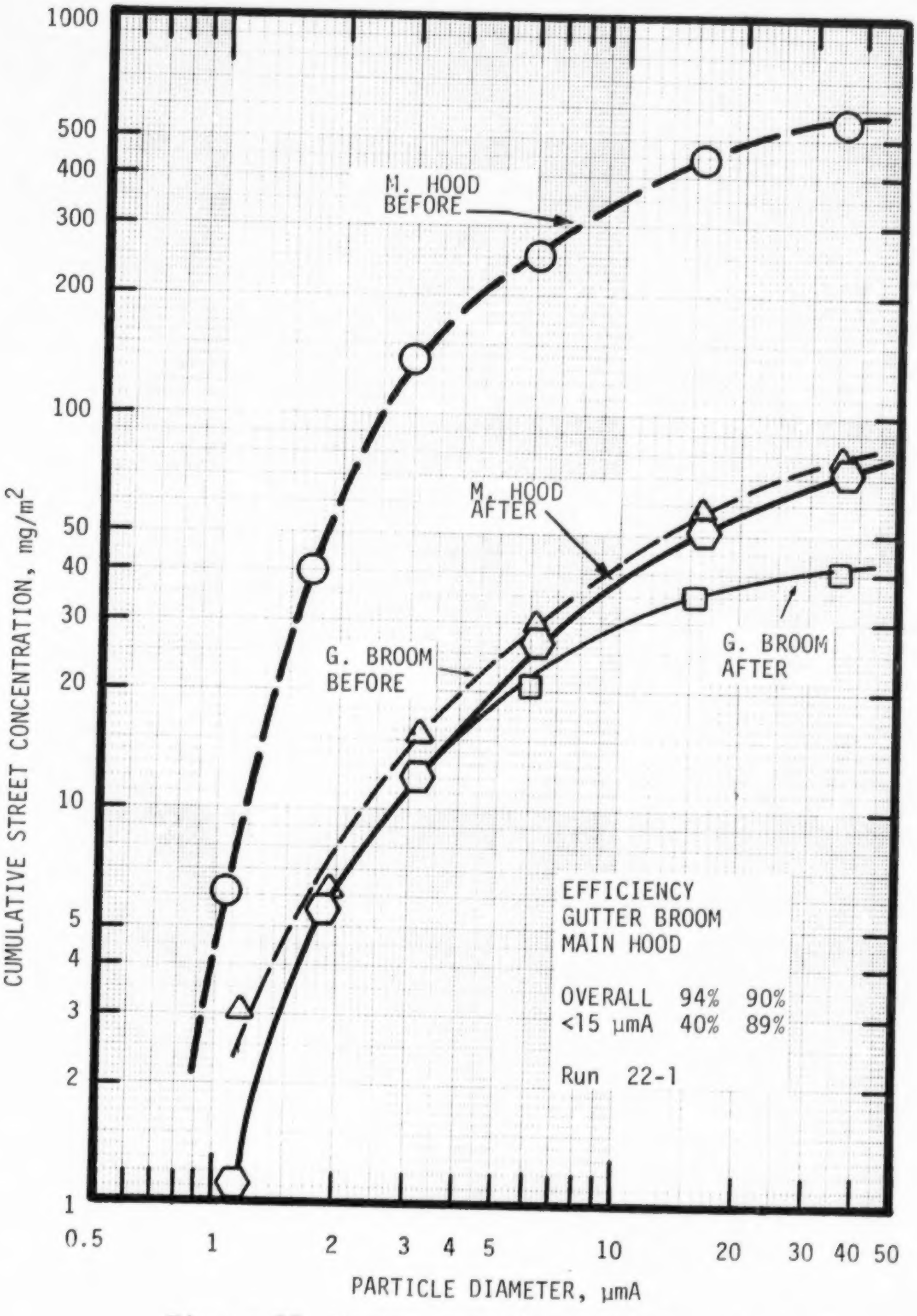


Figure 53. Street sweeping efficiency.

TABLE 14. SUMMARY OF SCRUBBER TESTS

RUN NO.	AIR FLOW, RATE m³/min	LIQUID/GAS, ℓ/m³	DUST CONCENTRATION[1], mg/DN m³		EFFICIENCY, %	
			Inlet	Outlet	Overall	<15 μm A
22/06	20.1	0.68	1036.13	206.94	80%	76%
22/07	20.1	0.68	1676.66	313.24	81%	77%
22/08	20.1	0.60	824.87	205.38	75%	72%
22/10	20.1	0.60	726.09	129.27	74%	70%
22/11	32.0	0.38	582.24	157.90	73%	67%
22/12	32.0	0.38	488.31	123.03	75%	70%

---

[1] Test Dust was Lime with MMD = 2.0 μm A and $\sigma_g = 2$.

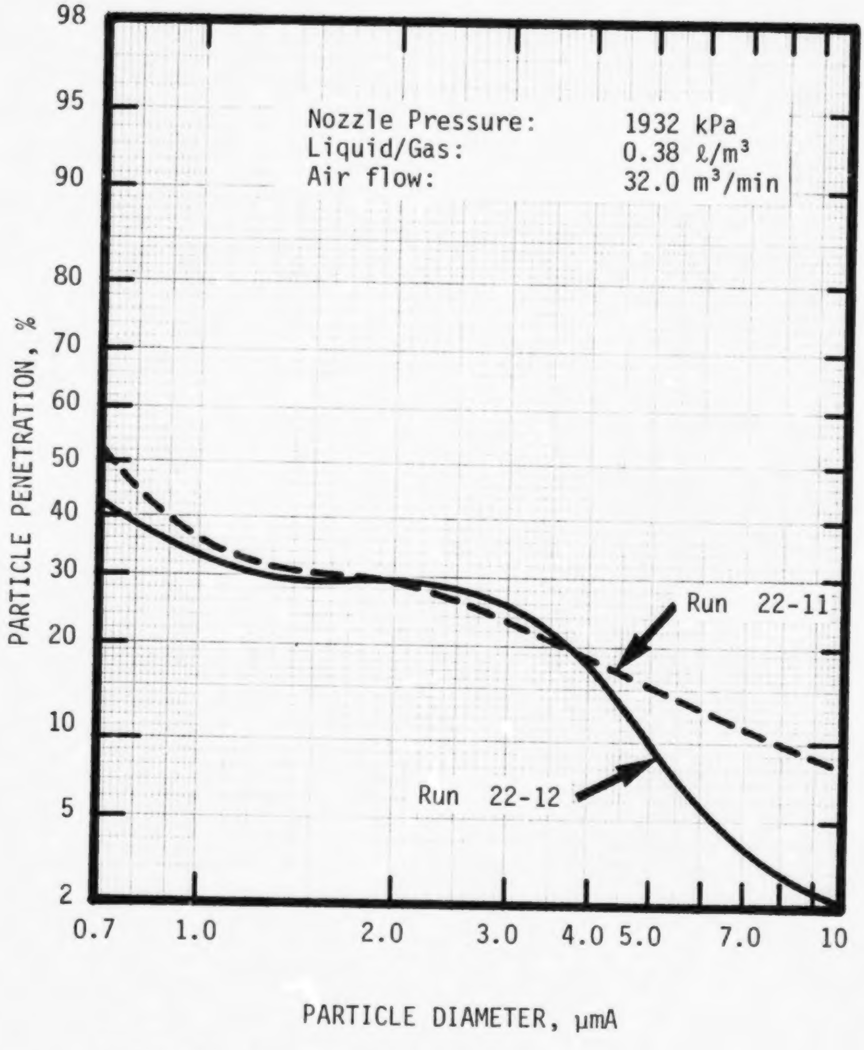


Figure 54. Scrubber Performance

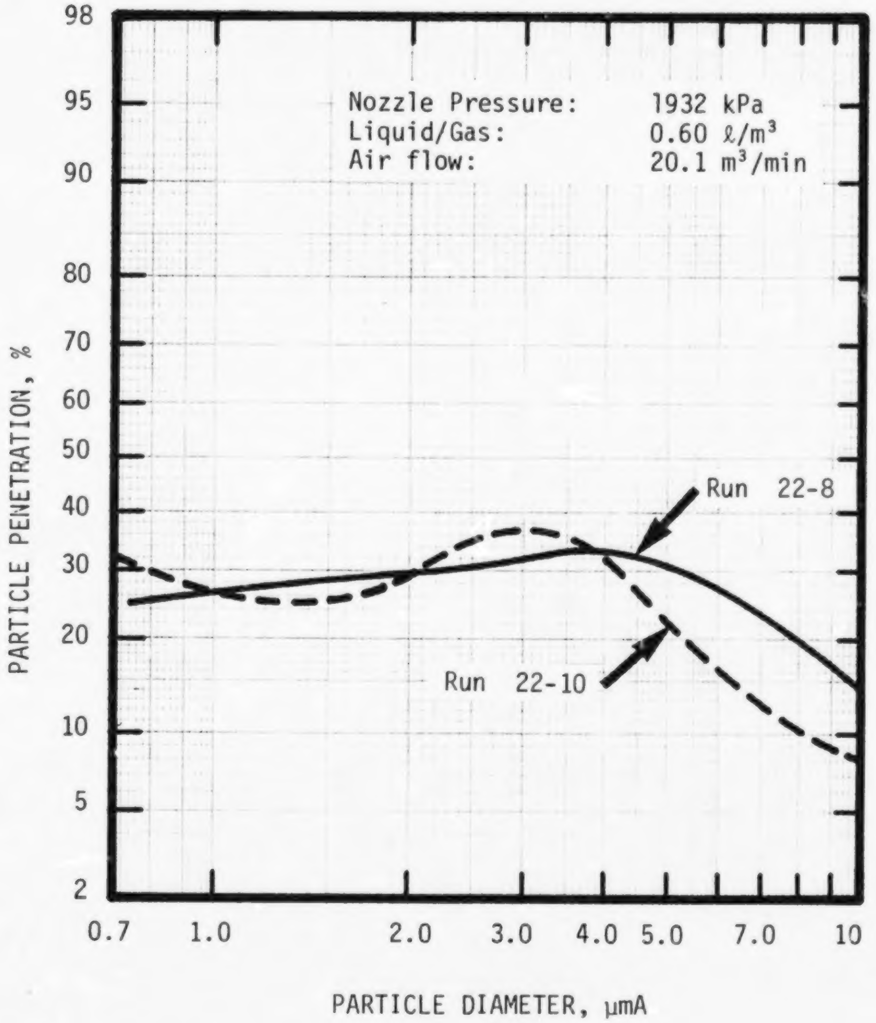


Figure 55. Scrubber Performance

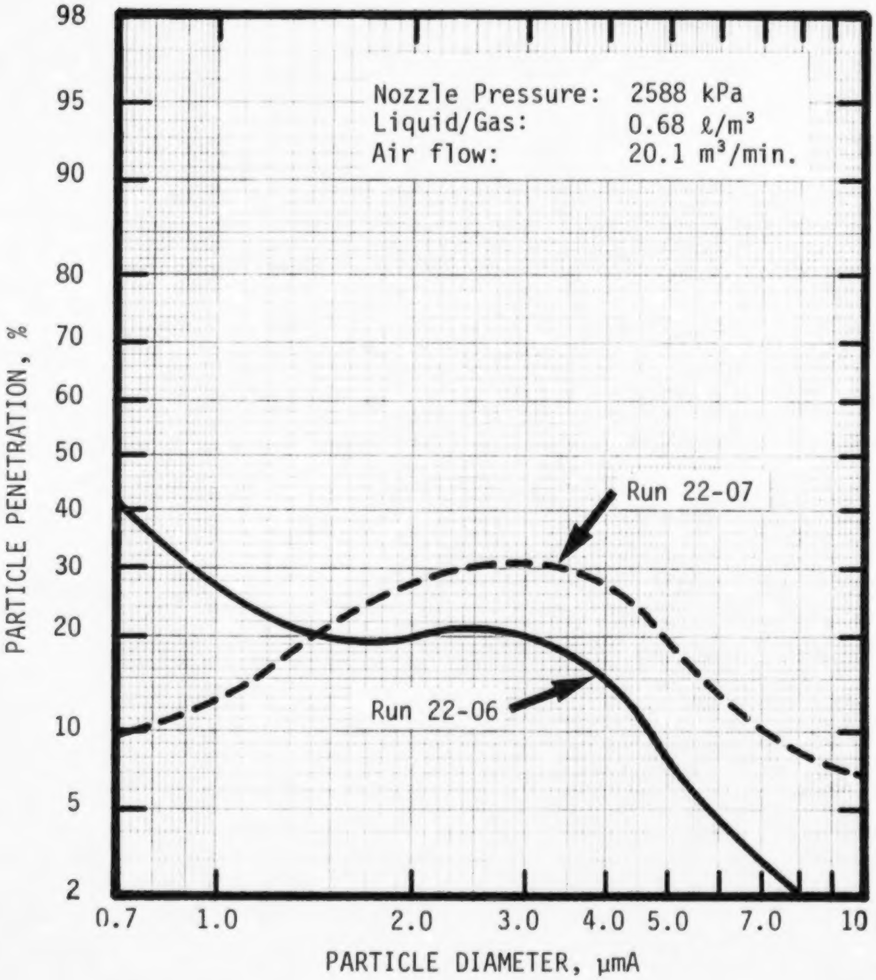


Figure 56 . Scrubber Performance.

CONCLUSIONS

The objective of demonstrating the feasibility of applying "Spray Charge and Trap" (SCAT) to the control of fugitive road dust emissions was proven. However, it also concluded that a Venturi scrubber should offer improved performance with less complexity for this application. A regenerative vacuum sweeper is ideally suited to a scrubber technique since it allows a discharge stream of air to be cleaned and recycled into the atmosphere. This feature reduces the size and power requirements for control of fugitive emissions of inhalable particle emissions.

Gutter broom dust emissions can be substantially improved with an advanced, interactive gutter broom hood. Since most of the dirt is in the gutter, this improvement is very significant. Additional power requirements for the SCAT system are minimal. Existing standard equipment pumps and blowers are sufficient to do the job.

Even though the current research work was done on a regenerative air vacuum sweeper, the same technology can be applied to a mechanical broom sweeper. Modifications to the mechanical sweeper will be more complicated since a blower needs to be installed on the sweeper to provide the suction air flow.

The cost for modifying a regenerative air vacuum sweeper was estimated to be about $2,000 which was about 5% of the sweeper cost. The cost to modify a mechanical sweeper will be higher because of the requirement of a blower.

Section 7

RECOMMENDATIONS

A superior street sweeping machine has been developed for reducing particle emissions from paved streets. This street sweeper has been subjected to a limited testing program in San Diego and Los Angeles. Results clearly indicate that the sweeper can eliminate the dust plumes during sweeping and give a cleaner street. However, additional research would refine the design and demonstrate its capability in improving the ambient air quality. The following studies would provide valuable information for further study:

1. Refine the design of the scrubber and incorporate it inside the hopper.
2. Improve the gutter broom sweeping efficiency for fine particles.
3. Demonstrate the sweeper on city streets and measure the improvement in ambient air quality.
4. Obtain more information on the nature of street dirt with respect to potential ambient air quality.
5. Use a smaller scrubber than the one presently installed. Results from this study indicated that an air vent rate of 14 m^3/min (1,000 acfm) was sufficient to eliminate the dust cloud in the gutter broom area. It is recommended that a low pressure drop Venturi scrubber be used instead of a charged spray scrubber because the wall loss of spray will be high for a small scrubber.

REFERENCES

Axetell, D., and T. Zell. "Control of Reentrained Dust from Paved Streets." U.S. Environmental Protection Agency, Washington DC, NTIS. PB 280325, July 1977.

Brookman, E. T., and D. K. Martin. "Assessment of Methods for Control of Fugitive Emissions from Paved Roads." EPH-600/7-79-239 (NTIS PB80-139330), Nov. 1979.

Brookman, E. T., and D. K. Martin. "Definition of a Methodology for the Evaluation of Road Dust Control Techniques." EPA-lERL Process Measurements Branch, Research Triangle Park, N.C., April 1979.

Buchwald, H., and K. R. Schrag. "Dust Exposure in Mechanical Street Sweepers." J. of A.I.H.I., 28, pp. 485-487, 1967.

Cowherd, C., C. M. Maxwell, and D. W. Nelson. "Quantification of Dust Entrainment from Paved Roadways." U.S. Environmental Protection Agency, Washington DC, EPA-450/3-77-027, NTIS PB 272613, July 1977.

Dahir, S. H., and W. E. Meyer. "Bituminous Pavement Polishing." The Pennsylvania State University, University Park, Pa., Nov. 1974.

Draftz, R. "The Impact of Fugitive Dust Emissions on TSP Concentrations in Urban Areas." In Third Symposium on Fugitive Emissions: Measurement and Control, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/7-79-182 (NTIS PB 80-130891), August 1979.

Horton, J. P. "Broom Life Isn't the Most Important Cost..." The American City, Buttenheim Publishing Co., New York, NY. July 1968.

Pitt, R. "Demonstration of Non-Point Pollution Abatement Through Improved Street Cleaning Practices." EPA-600/2-79-161. August 1979.

Roberts, J. W., A. T. Rossano, P. T. Bosserman. G. C. Hofer, and H . A. Watters. "The Measurement, Cost and Control of Traffic Dust and Gravel Roads in Seattle's Duwamish Valley." Paper No. AP-72-5, Presented at the Annual Meeting of the Pacific Northwest International Section of the Air Pollution Control Association, Eugene, Oregon, November 1972.

Sartor, J. D., G. B. Boyd, and W. H. Horn. "How Effective is Your Street Sweeper", APWA Reporter, April 1972.

Sartor, J. D., and G. B. Boyd. "Water Pollution Aspect of Street Surface Contaminants." U.S. Environmental Protection Agency Publication No. EPA-R2-72-081. 1972.

Steward. The Resuspension of Particulate Material from Surface Contamination, edited by B. R. Fish, Oxford, England, Pergamon Press, 1964.

URS Research Company. "Water Quality Management Planning for Urban Runoff." NTIS PB 241689/LK, December 1974.

Yung, S. C., J. Curran, and S. Calvert. "Spray Charging and Trapping Scrubber for Fugitive Particle Emission Control." EPA-600/7-81-125, NTIS PB82-115304, July 1981.